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HIGH VOLTAGE BREAKDOWN STUDY

W.R. Bell, et al

Ion Physics Corporation
Burlington, Massachusetts

December 1967

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HIGH VOLTAGE BREAKDOWN STUDY

ELEVENTH QUARTERLY PROGRESS REPORT

16 May 1967 through 15 August 1967

Prepared by:

ION PHYSICS CORPORATION
BURLINGTON, MASSACHUSETTS

DECEMBER 1967

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Technical Report ECOM-00394-11 December 1967

HIGH VOLTAGE BREAKDOWN STUDY

Eleventh Quarterly Progress Report

16 May 1967 through 15 August 1967

Report No. 11

Contract DA-28-043-AMC-00394(E)

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FORT MONMOUTH, NEW JERSEY 07703

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PURPOSE

The factors influencing breakdown in high voltage vacuum devices will be studied. The information obtained will provide the basis for improvement in the design of microwave and modulator tubes that must operate at voltages greater than 100 kilovolts without breakdown.

ABSTRACT

The block of eight experiments was completed during the reporting period. This consisted of the study of unconditioned and conditioned gaps in the range 0.25 to 3.0 cm and a parallel experiment to study the effect of the presence of magnetic field. Both physical and statistical analyses of the results have been carried out and have yielded very interesting trends which are consistent with the theories developed. The 300 kv apparatus has been completely overhauled and cleaned. The chamber and flanges were electro-polished, the electrode system redesigned and the bakeable bushing replaced. The Universal Voltronics and Van de Graaff power supplies were also overhauled and new baking and pumping systems designed, installed and commissioned. The new baking system provides for a consistent automated baking cycle for all future treatments. The design of the trigger unit for the energy storage crowbar has been completed. Finally, the preliminary design and selection of factors for the next experiment has been initiated.

LECTURES, CONFERENCES AND PUBLICATIONS

Lectures and Conferences

9, 20 May 1967

M. J. Mulcahy visited Fort Monmouth to attend the Third High Power Microwave Tube Symposium sponsored jointly by USAECOM and the IEEE. Discussions on the design of the block experiment were also held with G. Taylor, M. Zinn, M. Chrepta and J. Weinstein.

26, 27 June 1967

A. Watson visited Washington, D.C. to attend the Fourteenth Field Emission Symposium sponsored by the American Institute of Physics.

12 July 1967

G. Taylor (Fort Monmouth) visited Ion Physics Corporation to discuss the progress of the block experiment and the effect of applying the magnetic field both parallel and perpendicular to the electric field.

9, 10 August 1967

M. J. Mulcahy, W. R. Bell, A. S. Denholm and A. Watson (IPC) and M. M. Chrepta (Fort Monmouth) visited Washington, D. C. to review progress under the contract for Dr. Little and Dr. Smith at NRL and Mr. M. Witow at ARPA.

14 August 1967

Professor H. Freeman visited IPC to discuss the statistical analysis of the block experiment. M. Mulcahy, W. R. Bell and A. Watson were present.

Publications

There were no publications during this reporting period.

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SECTION 1

INTRODUCTION

The work reported herein describes the eleventh three months of a study of high voltage breakdown in vacuum with particular reference to problems encountered in the development of high power vacuum tubes.

The objectives of the period were to maintain the 300 kv system in an operational state while completing the block of eight experiment; to analyze the results of the block of eight experiment; to completely overhaul, repair and commission the 300 kv apparatus and components; and to initiate the design of the next experiment.

1.1 300 kv System

The 300 kv system was maintained in an operational state until the termination of the block of eight experiment, when it was disassembled for complete overhaul. The vacuum chamber was electro-polished and all gold O-ring surfaces refinished and polished. Redesign of the electrode support and adjustment mechanism has been completed which will remove the heaters and thermocouples from the vacuum envelope. The blanket oven has been installed and commissioned, complete with automated baking cycle control. In addition, the rotary and blower backing pumps have been replaced with oil free gas sorption and venturi pumps and the whole pump system has been relocated to increase the arc travel of the magnetic field coils. Finally, both high voltage power supplies and the control and monitoring instrumentation have been overhauled in readiness for the next experiment.

1.2 Block of Eight Experiment

The block of eight experiment has been completed and the results analyzed both on a physical and statistical basis. These analyses provide significant information both on the main factor effects of electrode area, processing and magnetic field and also on the interaction of two or more factors. Perhaps, of greater importance was the confidence level of the results which showed that the experimental control was excellent.

1.3 Experimental Design

Factors and levels for the next experiment have been examined and a preliminary selection has been made. This also includes the experimental design, and at the moment this looks like a half-factorial 6-factor experiment involving 32 treatments which can be split up in two blocks of 16. In addition to

the 6 inflexible factors parallel stacking of flexible factors such as magnetic field will increase the scope of the experiment, just as in the case of the block of eight experiment.

SECTION 2

300 KV TEST VEHICLE

2.1 Vacuum Chamber

During the reporting period the block of eight experiment was completed despite some vacuum leaks which occurred during the chamber bake and were mainly caused by failure of the electrical feedthroughs for the electrode heaters and thermocouples. This problem was temporarily solved by replacing all existing feedthroughs with a new type recently obtained from the manufacturer. In addition, modified designs of the electrode support structures have been completed. These will remove the electrode heaters and thermocouples from the vacuum envelope. The detail of one of these, namely the modification to the bottom electrode and bakeable bushing is shown in Figure 1. This includes a 'quick-connect-disconnect' fitting which will considerably reduce the time taken to install the electrodes in the chamber - a very important consideration in view of the need to minimize contaminates in the system. Fabrication has been completed and it was checked out by baking to 500°C in the vacuum oven. Apart from slight problems due to vacuum welding of two of the surfaces, which have been corrected for, the unit functioned satisfactorily and is currently being installed on the bakeable column in readiness for the next experiment. Fabrication of the corresponding unit for the top electrode is held up due to long delivery of special ceramic insulators.

Upon completion of the block of eight experiment the vacuum chamber was completely disassembled for thorough overhaul and cleaning. All gold O-ring surfaces were machined and polished and both the chamber and flanges were electro-polished. After assembly and bakeout, pressures in the low 10^{-9} torr range were obtained with the improved pumping assembly described below.

2.1.1 Pumping System

The pumping system was redesigned as outlined below and as shown in Figure 2 to optimize the overall pumping operation and to eliminate both the blower and rotary roughing pumps.

The roughing system consists of one Varian Gasp pump and two Varian Sorption pumps which are isolated from the main chamber by means of a Varian 1-1/2 inch bakeable right angle valve. The Gasp pump is a gas operated venturi type pump with a base pressure capability of 125 torr. The Sorption pumps are a molecular sieve type pump which require liquid N_2 to activate. This type pump has a base pressure capability of 1 x 10^{-2} torr.

The main pumping system consists of one General Electric 500 L/S triode ion pump with a base pressure capability of 10^{-12} torr. Pressure

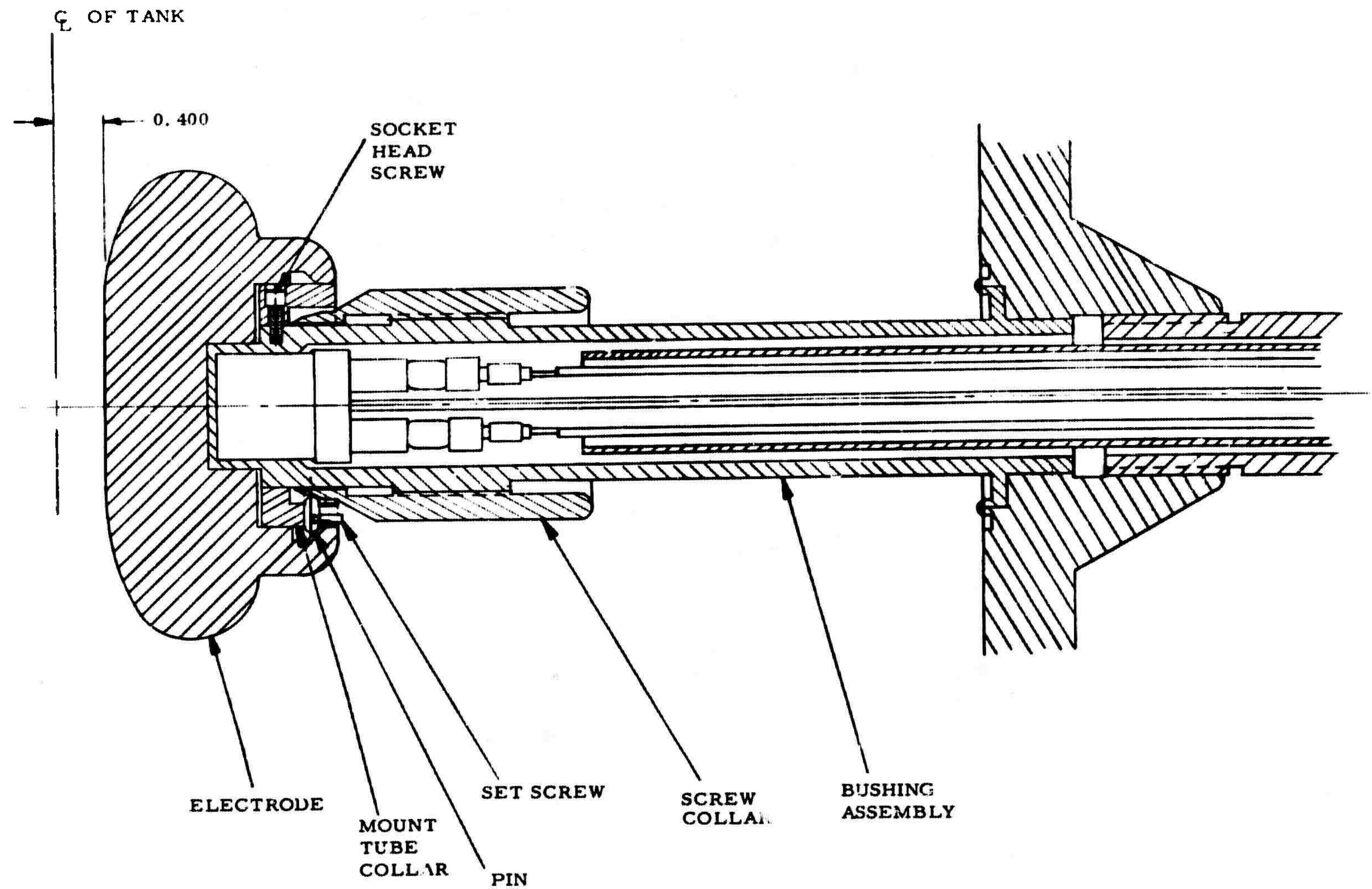

Figure 1. Bottom Electrode Support with Quick Disconnect Mechanism

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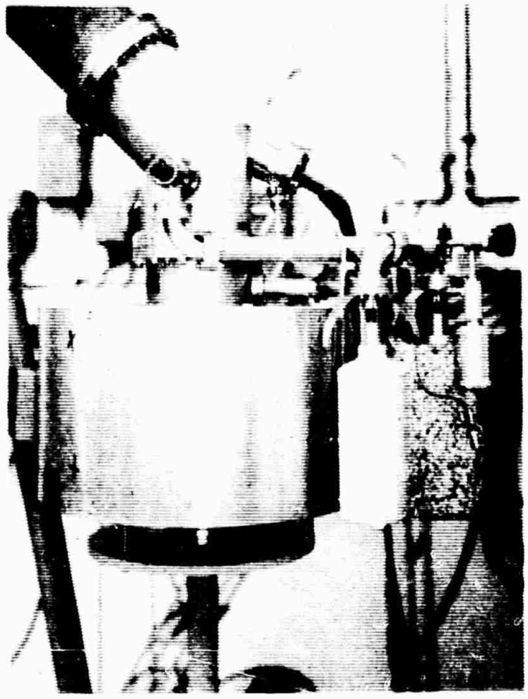

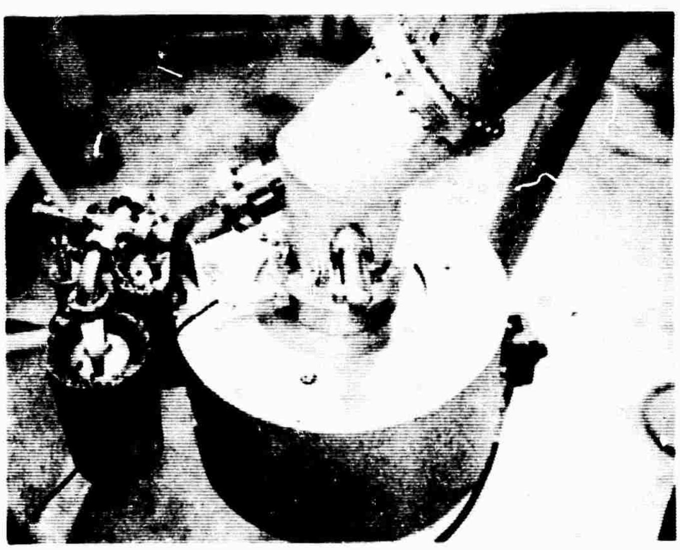

Figure 2. Modified Pumping System

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readings are taken by means of two Aero-Vac RGA heads mounted one in the pumping throat and the other in the main chamber.

To pump from atmosphere, the gas supply is turned on to the Gasp pump and the Sorption pump containers filled with liquid N_2. In approximately 15 minutes the main chamber pressure is down to 125 torr and the Gasp pump isolation valve is closed. The Sorption pumps continue to pump the chamber. In approximately 12 to 15 minutes after the Gasp pump is valved off the pressure in the main chamber is down to 10 microns. At this point the Ion pump is turned on. When the pressure in the main chamber is down to approximately 8×10^{-4} torr the Sorption pumps are valved off from the chamber and allowed to warm up to room temperature. Before system bakeout the pressure is in the high 10^{-8} torr range, afterwards low 10^{-9} torr pressure is achieved in the chamber.

The Gasp pump may also be used to de-gas the Sorption pumps if so desired.

2.1.2 Feedthrough Bushing

The bakeable column which was used throughout both the pilot and the block of eight experiment has undergone about 50 bakeouts and has therefore been replaced. The new column has been modified to accept the electrode support mechanism shown in Figure 1. The old column will serve as an emergency replacement but since it has already well exceeded its lifetime in terms of heating cycles, a column will be designed and fabricated.

The unbakeable column as well as the dielectric insert and resistance grading chain have been thoroughly cleaned in readiness for the next experiment.

2.1.3 Bakeable Leak Valve

As indicated in Section 2. [illegible] a Varian bakeable leak valve was installed on the vacuum pumping line. This is of welded stainless steel construction, it has a positive control with no backlash in the drive mechanism and can consistently control leaks as small as 1×10^{-10} torr-liters per second.

2.2 High Voltage Power Supply

Modifications were made to ensure correct mechanical action of the grounding switch. These consisted of changing the pivot point and also inserting a V-grooved section of lucite to limit its travel. No further problems were encountered of overheating of the activating solenoid or damage to the resistor chain.

The Van de Graaff power supply was also completely cleaned, overhauled and made fully operational in readiness for checking out of the energy storage system and for side experiments.

For the next experiment it is planned to operate with the T-piece in place and the same cable length as will be used with the energy storage connected. This will keep any cable transit times constant and so isolate the effect of energy storage when the latter is added. The T-piece is merely a pressure junction box for 3 high voltage bushings with connections for the high voltage power supply, the vacuum chamber and the energy storage system.

2.3 Baking System

The new heating mantle described in the previous Quarterly Progress Report was installed and the system was baked for 16 hours blanked off, i.e., without electrode structure or bushing. No problems were encountered. The baking cycle for the next experiment will be completely automatic to ensure uniformity of preparation for the various treatments. Accordingly, the following control instrumentation and safety devices have been installed:

(1) Control: Mantle power is controlled by a West controller-recorder which brings the chamber up to temperature (350 to 400°C) in 2 hours and continuously records the temperature using thermocouples located at the viewpoint. For the electrode heaters which operate at 50 v and 0.5 amp two separate controller-recorders will similarly control and record the temperature of each.

(2) Safety: The power is automatically cut off when the temperature reaches the pre-set value. Thereafter it is alternately switched off or on and during the test bake the temperature was maintained within 5°C of the pre-set value. The power is also shut off it the thermocouple breaks, if the ion pump pressure should rise over 1×10^{-5} torr or if the current to either of the two valves of the baking mantle changes by more than 15%. This latter safeguard protects against one of the heaters opening up or being shorted out, in which case serious temperature gradients would occur.

To date all controllers, recorders, thermocouples and other safety devices have been calibrated and commissioned. It is anticipated that all this will completely standardize the baking cycle as well as reduce the overall time by about 12 hours.

2.4 Instrumentation

A prototype transient current monitor has been constructed and will be tried out on the 300 kv system. It is anticipated that this will indicate the current/time development from microamps to amps.

This will be an additional measurement of electrode-gap parameters during application of voltage breakdown. The others are:

- Total X-radiation
- Collimated X-radiation
- Gap current
- Partial and total pressure
- Current and voltage waveshape

2.5 Magnetic Field System

This has been commissioned, installed and has operated satisfactorily. The location of the ion pump was found to limit the crossed coil field position such that the maximum horizontal field attainable was 250 gauss (0.025 Wb/M^2) at the electrodes. This has now been changed as shown in Figure 2 to free the coil movement so that 350 gauss is now attainable.

2.6 Energy Storage System

The trigger assembly for the vacuum crowbar which meets the requirements of General Electric has now been constructed and tested and awaits commissioning on the energy storage system. The design is given in the previous Quarterly Progress Report.

2.7 Electrode Systems

2.7.1 Electrode Preparation

The complete method of electrode fabrication and preparation is as follows:

(1) General: The electrodes are machined and ground to a 600 grit silicon carbide finish using green soap and distilled water as a lubricant.

(2) Cleaning: They are then vapor degreased in trichloroethylene, ultrasonically cleaned in genesolv-D and finally vapor degreased in genesolv-D.

(3) Vacuum Firing: Electrodes are maintained at 900°C in vacuum ($< 3 \times 10^{-6}$ torr) for six hours and then allowed to cool to ambient still under vacuum, at which stage the pressure is about 5×10^{-9} torr. The electrodes are then transported in a dry nitrogen atmosphere to the test chamber.

(4) Hydrogen Firing: Preliminary tests - Preliminary tests are carried out in which electrodes were fired in vacuum for 6 hours at 900°C prior to hydrogen firing. This is done because earlier vacuum fired small electrodes had been vacuum etched and it is hoped to produce the same electrode surface structure. Vacuum firing later with large electrodes did not produce this effect and so it was decided to simply fire in hydrogen which is in keeping with high power vacuum tube practice. The firing cycle is as follows: the retort is evacuated and the pure hydrogen introduced at a positive chamber pressure of a few inches of water and the electrodes baked at 900°C for 6 hours. The hydrogen flow is maintained during cooling to 250°C and is followed by pure nitrogen cooling to 50°C. (Both hydrogen and nitrogen are maintained in a dry state using the arrangement shown in Figure 3.)

2.7.2 Assembly and Installation

The new assembly described in Section 2.1 and shown in Figure 1 will enable the electrodes to be quickly and easily installed and removed from the vacuum chamber and will also remove the heaters and thermocouples from the vacuum envelope, thus eliminating all feedthroughs.

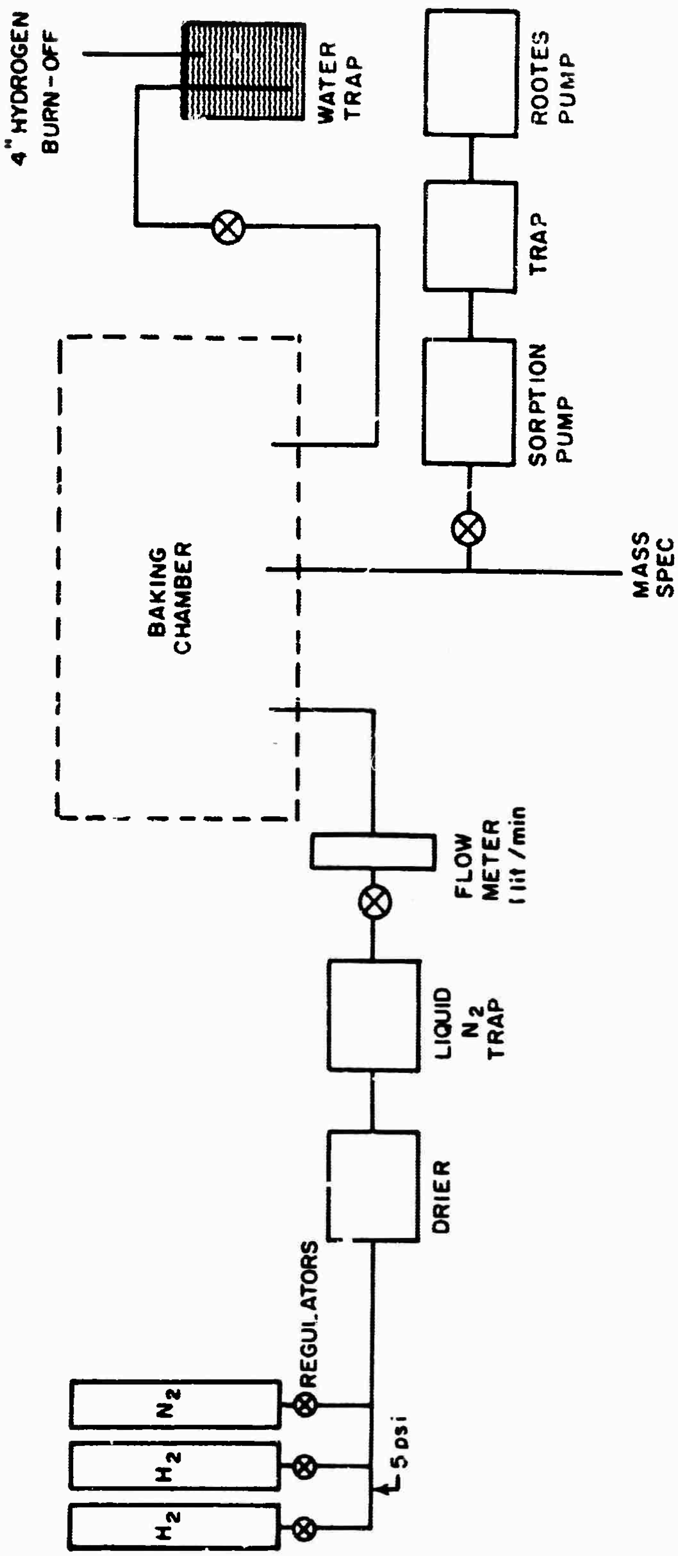

Figure 3. Hydrogen Firing System

SECTION 3

THE BLOCK OF EIGHT EXPERIMENT

3.1 General

The block of eight experiment has now been completed together with two replications which were necessary because of slight modifications to the procedure. The factors, levels and order of treatments are shown in Tables 1, 2 and 3. As outlined in the previous Quarterly Progress Report a parallel block experiment was also carried out with magnetic field perpendiculat to the electric field. This provided information as follows on:

(1) The effect of the factors in the presence of the magnetic field.

(2) The interaction between the factors and the magnetic field.

(3) The magnitude of the magnetic field effect as a function of the 3 inflexible factors and the gap length.

In addition to the parallel block or stacked experiment runs were carried out for selected treatments in order to checkout theories, techniques or procedures such as the gas exposure test described in the next section.

3.2 Procedure

This has been described previously, but is included to illustrate a typical series of checkout runs which were carried out in addition to the main and stacked magnetic field treatments, see Table 4.

(1) Three breakdowns at 1 cm gap followed by one breakdown at each higher gap setting up to 3.0 cm each lower gap setting down to 0.25 cm in increments of 0.25 cm. This gives the unconditioned values, column 1.

(2) The sequence was repeated to give the conditioned breakdown voltages, column 2. This definition of conditioned is arbitrary but has the merit of being consistent for each gap, i.e., 12 more sparks precede it than for the unconditioned value.

(3) For 0.5 cm gap increments breakdown measurements were taken without, with and without perpendicular

Table 1. Factors and Levels for Block Experiment Without Magnetic Field

		Level	
Factor	Letter	High	Low
Anode Processing	A	a - Vacuum Baked	1 - Hydrogen Baked
Cathode Processing	B	b - Vacuum Baked	1 - Hydrogen Baked
Electrode Size	C	c - Large	1 - Small

Table 2. Factors and Levels for Block Experiment With Magnetic Field

		Level	
Factor	Letter	High	Low
Anode Processing	A	a - Vacuum Baked	1 - Hydrogen Baked
Cathode Processing	B	b - Vacuum Baked	1 - Hydrogen Baked
Electrode Size	C	c - Large	1 - Small
Perpendicular Magnetic Field	D	d - Present	1 - Absent

Table 3. Experimental Order

Order	Description	Main Block	Perpendicular Fields
1	Anode 4 Inch Bruce H-Bake Cathode 4 Inch Bruce H-Bake	c	cd
2	Anode 4/3 Inch Bruce H-Bake Cathode 4/3 Inch Bruce H-Bake	(1)	d
3	Anode 4 Inch Bruce Vac-Bake Cathode 4 Inch Bruce H-Bake	ac	acd
4	Anode 4/3 Inch Bruce Vac-Bake Cathode 4/3 Inch Bruce Vac-Bake	ab	abd
5	Anode 4/3 Inch Bruce H-Bake Cathode 4/3 Inch Bruce Vac-Bake	b	bd
6	Anode 4 Inch Bruce H-Bake Cathode 4 Inch Bruce Vac-Bake	bc	bcd
7	Anode 4 Inch Bruce Vac-Bake Cathode 4 Inch Bruce Vac-Bake	abc	abcd
8	Anode 4/3 Inch Bruce Vac-Bake Cathode 4/3 Inch Bruce H-Bake	a	ad

Table 4. Sequence of Breakdown Measurements for Treatment bc(d)

bc		bcd	
Unconditioned	Conditioned	Magnetic Field ($\overline{H}$)	
1.0 cm (1)	1.0 cm (27)	1.0 cm w/o $\overline{H}$ (28)	2.0 cm w/o $\overline{H}$ (46)
1.0 cm (2)		1.0 cm w $\overline{H}$ (29)	2.0 cm 1/6 $\overline{H}$ (47)
1.0 cm (3)	1.0 cm (15)	1.0 cm w/o $\overline{H}$ (30)	2.0 cm 1/3 $\overline{H}$ (48)
1.25 cm (4)	1.25 cm (16)	1.5 cm w/o $\overline{H}$ (31)	2.0 cm 1/2 $\overline{H}$ (49)
1.5 cm (5)	1.5 cm (17)	1.5 cm w $\overline{H}$ (32)	2.0 cm 2/3 $\overline{H}$ (50)
1.75 cm (6)	1.75 cm (18)	1.5 cm w/o $\overline{H}$ (33)	2.0 cm 5/6 $\overline{H}$ (51)
2.0 cm (7)	2.0 cm (19)	2.0 cm w/o $\overline{H}$ (34)	2.0 cm w $\overline{H}$ (52)
2.25 cm (8)	2.25 cm (20)	2.0 cm w $\overline{H}$ (35)	2.0 cm w/o $\overline{H}$ (53)
2.5 cm (9)	2.5 cm (21)	2.0 cm w/o $\overline{H}$ (36)	2.0 cm 1/6 $\overline{H}$ (54)
2.75 cm (10)	2.75 cm (22)	2.5 cm w/o $\overline{H}$ (37)	2.0 cm 1/3 $\overline{H}$ (55)
3.0 cm (11)	3.0 cm (23)	2.5 cm w $\overline{H}$ (38)	2.0 cm 1/2 $\overline{H}$ (56)
0.75 cm (12)	0.75 cm (24)	2.5 cm w/o $\overline{H}$ (39)	2.0 cm 2/3 $\overline{H}$ (57)
0.50 cm (13)	0.5 cm (25)	3.0 cm w/o $\overline{H}$ (40)	2.0 cm 5/6 $\overline{H}$ (58)
0.25 cm (1[illegible]	0.25 cm (26)	3.0 cm w $\overline{H}$ (41)	2.0 cm w $\overline{H}$ (59)
		3.0 cm w/o $\overline{H}$ (42)	
		0.5 cm w/o $\overline{H}$ (43)	
		0.5 cm w $\overline{H}$ (44)	
		0.5 cm w/o $\overline{H}$ (45)	

Exposure I and $\overline{H}$	Reversed $\overline{H}$	Exposure II and $\overline{H}$
2.0 cm w/o $\overline{H}$ (60)	2.0 cm w/o $\overline{H}$ (75)	2.0 cm w/o $\overline{H}$ (85)
2.0 cm w/o $\overline{H}$ (61)	2.0 cm w $\overline{H}$ (76)	2.0 cm w/o $\overline{H}$ (86)
2.0 cm w/o $\overline{H}$ (62)	2.0 cm w/o $\overline{H}$ (77)	2.0 cm w/o $\overline{H}$ (87)
2.0 cm w/o $\overline{H}$ (63)	2.0 cm w $\overline{H}$ (78)	2.0 cm w/o $\overline{H}$ (88)
2.0 cm w $\overline{H}$ (64)		2.0 cm w/o $\overline{H}$ (89)
2.0 cm w/o $\overline{H}$ (65)	Regular $\overline{H}$	2.0 cm w/o $\overline{H}$ (90)
2.0 cm w/o $\overline{H}$ (66)	2.0 cm w/o $\overline{H}$ (79)	
2.0 cm w $\overline{H}$ (67)	2.0 cm w/o $\overline{H}$ (80)	Ion Pump Off
2.0 cm w/o $\overline{H}$ (68)	2.0 cm w/o $\overline{H}$ (81)	2.0 cm w/o H (91)
2.0 cm w $\overline{H}$ (69)	2.0 cm w/o $\overline{H}$ (82)	2.0 cm w H (92)
2.0 cm w/o $\overline{H}$ (70)	2.0 cm w $\overline{H}$ (83)	2.0 cm w/o H (93)
2.0 cm w $\overline{H}$ (71)	2.0 cm w/o $\overline{H}$ (84)	
2.0 cm w/o $\overline{H}$ (72)		
2.0 cm w $\overline{H}$ (73)		
2.0 cm w/o $\overline{H}$ (74)		

magnetic field and finally for different magnetic field strengths at a fix d gap setting of 2.0 cm, columns 3 and 4.

(4) This concluded the block and stacked magnetic field experiment. Columns 5, 6 and 7 refer to additional runs carried out to help determine procedures for gas exposure tests, the effects of reversed magnetic fields and also to examine the gas release from the electrodes. Thus, for gas exposure, the object was to determine what leak rate, pressure and time were appropriate for selected gases.

3.3 Results

3.3.1 Main Block

The results of the main block experiment are shown in Table 5. The order for carrying out the treatments was randomly chosen and is as follows:

(1), c, ab, ac, b, a, abc, bc

For each gap both unconditioned and conditioned breakdown voltages are included in the first and second columns, respectively. In the 1.0 cm case the figure above the diagonal refers to the very first breakdown, while the lower figure is the third breakdown value for the fresh electrodes.

3.3.2 The Effect of Magnetic Field

As discussed in the previous Quarterly Progress Report, problems were encountered when parallel magnetic fields were applied, in that when the voltage across the gap was raised, a heavy current drain on the power supply from the bushing to ground was experienced. At first this limited the maximum voltage to about 10 kv for magnetic field of 350 gauss, but subsequent conditioning increased the voltage attainable to greater than 100 kv. At the same time the pressure in the system rose about an order of magnitude from 10^{-8} to about 10^{-7} torr and an extensive glow discharge filled the chamber. These phenomena are curently being investigated.

Meanwhile the transverse magnetic field was applied without difficulty: there was no current drain except the gap current and no pressure rise. The usual test procedure, carried out at 6 gap separations from 0.5 to 3.0 cm yield the results of Table 6. For each gap the breakdown voltage was measured firstly without the magnetic field, secondly with it and finally without it again.

Table 5. Breakdown Voltage of Main Block Experiment for Different Gaps

Treatment	Gap (cm)																							
	1.0		1.25		1.5		1.75		2.0		2.25		2.5		2.75		3.0		0.75		0.5		0.25	
(1)	100 / 120	158	130	160	139	174	141	200	167	200	180	220	180	230	190	240	190	250	120	120	100	107	45	39
c	50 / 69	110	80	120	90	120	100	125	100	130	110	140	110	130	120	140	140	140	100	100	85	85	37	44
ab	56 / 50	110	70	128	77	120	70	120	80	120	80	130	90	140	99	140	110	160	70	80	57	80		
ac	67 / 70	100	79	130	90	147	100	130	105	130	127	140	130	160	114	180	150	150	69	90	39	69	25	26
b	64 / 80	155	100	170	131	180	130	190	160	190	170	210	190	220	160	200	216	200	115	145	90	127	61	60
a	80 / 90	160	90	160	109	170	135	170	150	180	166	187	170	200	180	216	160	206	90	119	83	100	49	44
abc	20 / 70	130	80	140	100	133	100	150	90	15[illegible]	120	160	120	150	143	129	140	140	29	107	90	90	38	30
bc	50 / 80	100	87	90	89	90	89	110	100	100	100	120	110	120	139	120	130	120	78	90	63	80	51	57

Table 6. Breakdown Voltages With and Without Transverse Magnetic Field for Different Gaps

Treatment	Gap (cm)																	
	1. 0			1. 5			2. 0			2. 5			3. 0			0. 5		
	w/o	w	w/o	w/o	w	w/o	w/o	w	w/o	w/o	w	w/o	w/o	w	w/o	w/o	w	w/o
(1)	152	140	160	190	200	200	200	217	220	230	230	250	270	240	260	98	100	100
c	90	100	110	120	130	130	130	127	130	149	150	130	150	150	140	79	97	100
ab	130	90	100	107	100	100	150	100	150	169	110	150	150	110	160	90	80	90
ac	129	70	100	140	88	150	160	80	170	170	90	179	200	90	140	86	74	85
b	115	120	170	191	150	199	220	160	220	230	180	240	245	180	240	95	130	130
a	150	130	160	160	130	140	190	160	170	210	170	200	190	170	200	95	99	110
abc	140	120	140	160	119	130	170	130	160	180	150	160	180	150	150	78	99	100
bc	90	90	95	120	120	118	130	120	140	140	130	130	150	150	170	78	110	110

3.3.3 Current Magnitude and Waveshape

The penultimate gap current was recorded in each case and also representative oscillograms of the collapse of voltage, using both voltage and current monitors. Preliminary examinations of the latter indicate not only that the time to collapse varies with gap spacing but also that the magnetic field changes slope of the oscillograms. This is being investigated and will be reported in the next Quarterly Progress Report.

3.3.4 Pressure Surges

An auxiliary side experiment was performed to investigate the effect of the weak transverse magnetic field on the voltage and current thresholds for the appearance of pressure surges. The system had been prepared for treatment (1), but was unable to be pumped below 10^{-7} torr and so was unacceptable for use in the statistical experiment. Instead, the breakdown voltage, threshold and prebreakdown currents were monitored for arc gap separations from 0.25 cm to 3.0 cm at 0.25 cm intervals with the magnetic field aternately present and absent.

It is shown in Figure 4 that the result was an increase in voltage threshold for pressure surges when the magnetic field was present but the current threshold was unaltered (Figure 5). Below 0.5 cm this was not the case and it is interesting that this crossover point of the curves is the same as that appearing on all of the curves of effects as a function of gap separation in the statistical experiment discussed in Section 4. This is further confirmation of the significance of pressure surges as precursors to gap failure.

1-2306

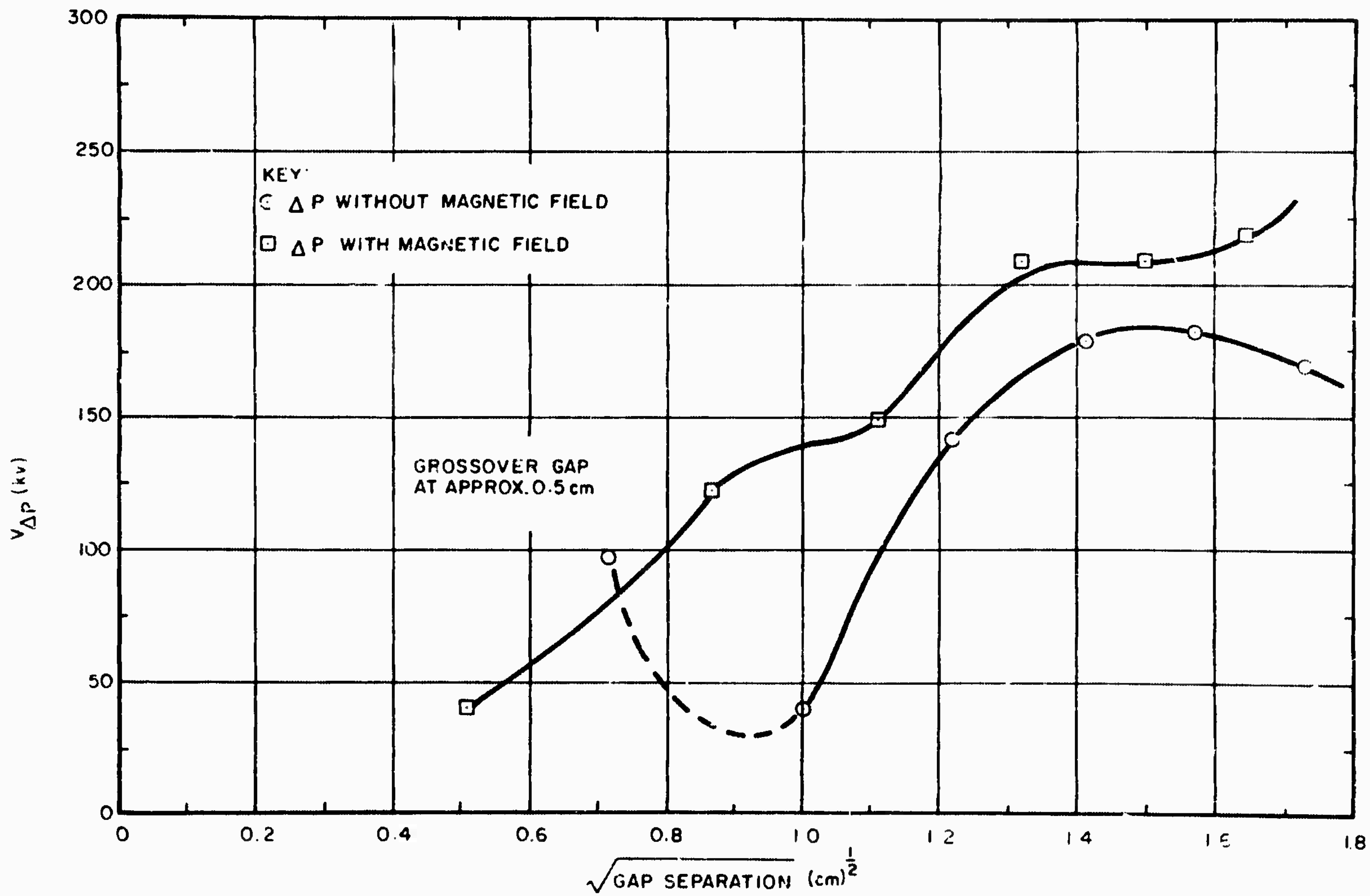

Figure 4. Variation of Voltage Threshold with Gap Length for Pressure Surges

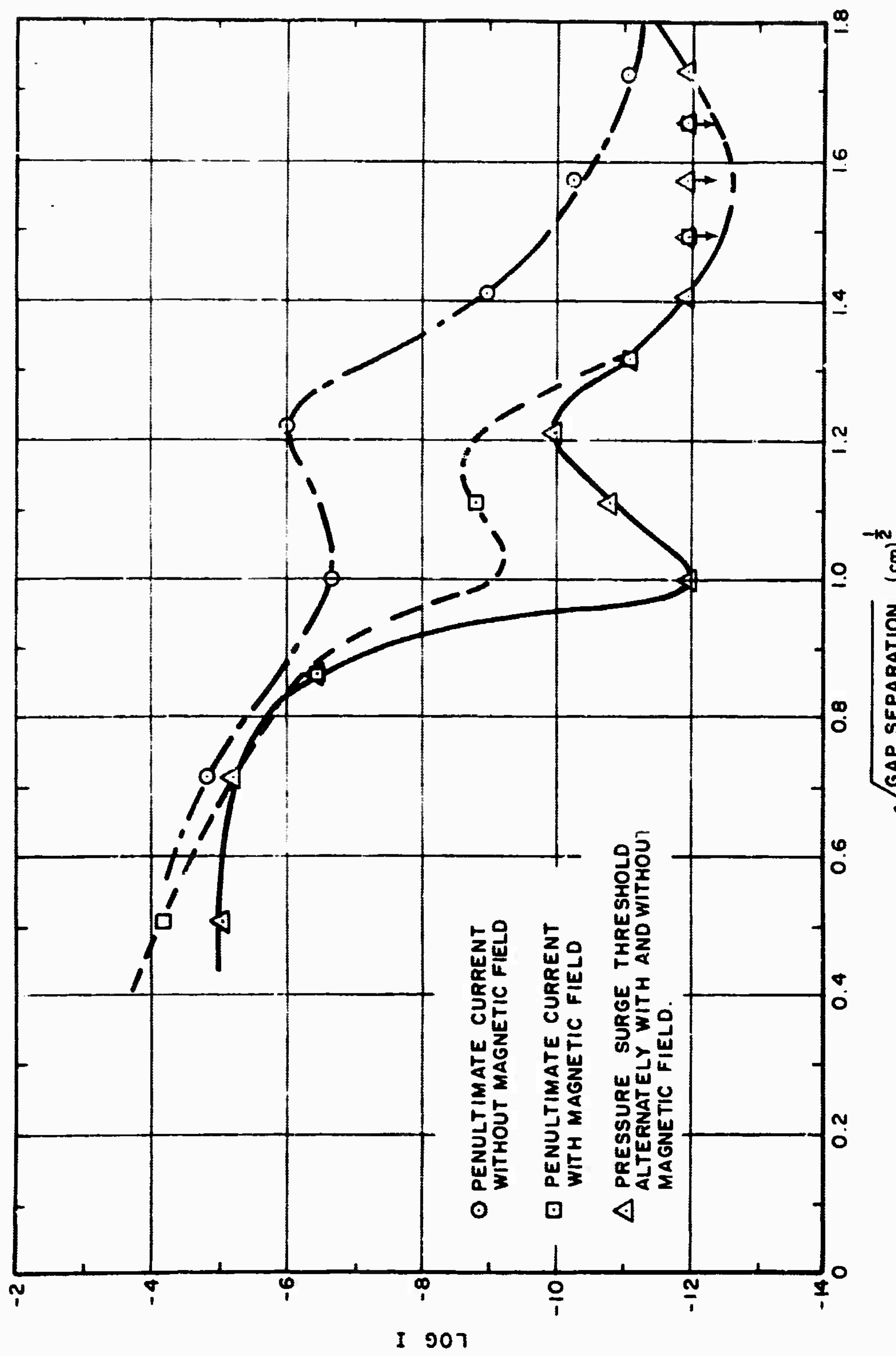

Figure 5. Variation of Current Threshold with Gap Length for Pressure Surges

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SECTION 4

ANALYSIS AND DISCUSSION

4.1 General

A Yates Algorithm analysis performed on the results yielded for the present full factorial experiment, estimates of all main effects and also all interactions, as well as the experimental mean. This method of analysis consists of repeatedly adding and subtracting adjacent test results once the treatments have been arranged in the standard Yates order, namely, (1), a, b, ab, c, ac, bc, abc. A full description of the process is given by O. D. Davies in "Design and Analysis of Industrial Experiments" (Hafner Publishing Co., N. Y.) 1963. Computer programs were drawn up to perform the operations and the resultant estimates of the experimental means, the factor and the interaction effects are given in Tables 7, 8 and 9 for the unconditioned, conditioned and magnetic field cases, respectively.

The following general conclusions may be drawn:

(1) Larger gaps are associated with higher breakdown voltages.

(2) The overall effect of the magnetic field was to reduce the average breakdown voltage.

4.2 Discussion of Factors and Interactions With and Without Magnetic Field

4.2.1 General

The data presented in Table 9 have been plotted in Figures 6 through 13. The effects of each factor shown up by subtracting the values A, B, AB, C, AC, BC, ABC individually from the corresponding overall average breakdown values μ. Thus, the effect of A is demonstrated by plotting (μ - **A**) and μ as functions of $d^{1/2}$ (square root of gap separation), since μ is almost a linear function of $d^{1/2}$. Similarly, the corresponding factors and interactions (denoted as AE, BE, ABE, CE, ACE, BCE, ABCE) are plotted along with the corresponding average breakdown voltage in the presence of the magnetic field (μE).

The subscripts 1 and 3 refer to the first and third column (under "no" headings) at each gap separation in Table 9. This has been done to show up any consistent difference between the first and third breakdown value (at each separation) which would be indicative of a memory of the conditions imposed by the magnetic field after it was removed.

Table 7. Estimates of Effects (kv) by Yates' Algorithm for Unconditioned Gaps Without Magnetic Field

Gap (cm)

			Upper	Lower								
	0.50	0.75	1.00	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00
μ	76	84	61	79	90	103	108	119	132	138	143	155
A	-17	-39	-10	-17	-20	-18	-14	-26	-17	-20	-16	-29
B	-2	-22	-27	-17	-11	-3	-22	-23	-28	-20	-16	-11
AB	14	-8	-9	-3	1	-3	-11	-20	-18	-25	-10	-19
C	-13	-30	-28	-13	-16	-22	-22	-41	-35	-40	-28	-29
AC	8	-1	4	13	16	24	19	23	35	35	17	39
BC	16	-9	3	23	15	12	16	16	20	15	40	1
ABC	22	-1	-15	-3	-4	9	16	12	20	20	15	19

Table 8. Estimates of Effects (kv) by Yates' Algorithm for Conditioned Gaps Without Magnetic Field

Gap (cm)

	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00
μ	93	106	128	137	142	149	151	163	169	171	171
A	-15	-15	-6	5	2	-14	-8	-18	-13	-9	-14
B	4	-2	-8	-11	-22	-14	-18	-17	-23	-47	-32
AB	-4	-9	-2	-1	-10	-1	2	-2	-13	-17	[illegible]
C	-23	-19	-36	-35	-39	-41	-43	-47	-58	-57	-67
AC	12	18	16	26	34	36	37	38	43	33	29
BC	4	5	18	1	0	16	17	17	13	11	17
ABC	17	23	22	21	18	19	27	22	13	1	22

Table 9. Estimates of Effects by Yates Algorithm for Conditioned Gaps With ("yes") and Without ("no") Magnetic Field

	0.05			1.00			1.50			2.00			2.50			3.00		
	no	yes	no	no	yes	no	no	yes	no	no	yes	no	no	yes	no	no	yes	no
μ	87	99	102	126	108	129	149	130	146	169	137	170	185	151	180	192	155	183
A	0	-21	-16	28	-10	-9	-14	-41	-32	-3	-39	-15	-5	-43	-15	-24	-50	-40
B	-4	12	11	-14	-5	-6	-8	-15	-18	-3	-19	-5	-10	-18	-20	-21	-15	-5
AB	-2	-9	-9	5	10	-4	-9	15	-12	-13	14	-10	-6	18	-15	-9	15	-10
C	-14	-7	-6	-27	-25	-36	-27	-31	-28	-43	-45	-40	-50	-43	-60	-44	-40	-65
AC	4	4	4	17	10	26	44	19	48	38	20	45	36	-23	55	64	20	30
BC	0	7	1	19	25	19	10	25	2	8	40	5	11	38	10	11	45	25
ABC	-1	15	11	1	20	31	19	5	8	18	15	0	15	23	5	-1	15	0

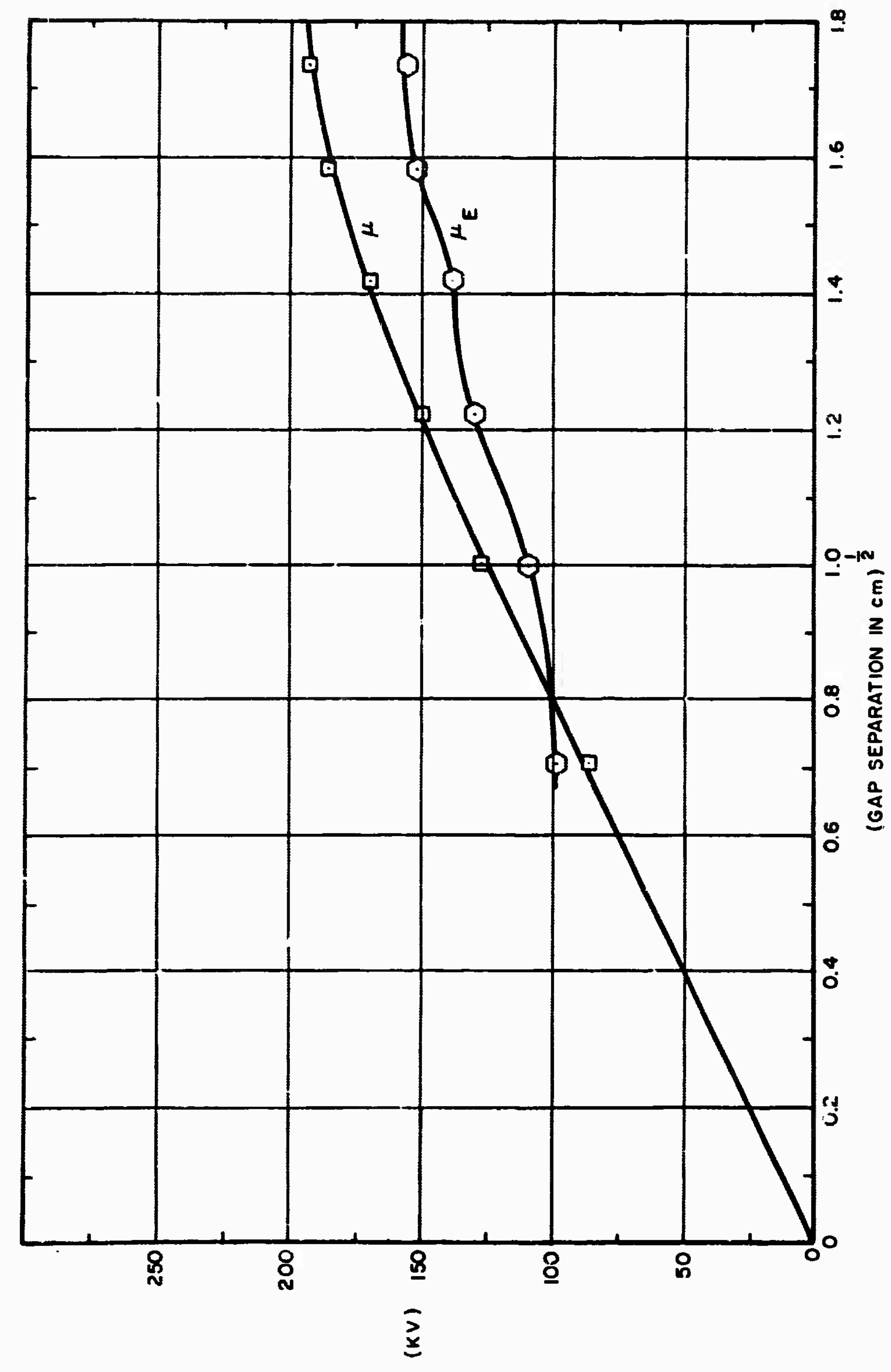

Figure 6. The Average Effect (μ)

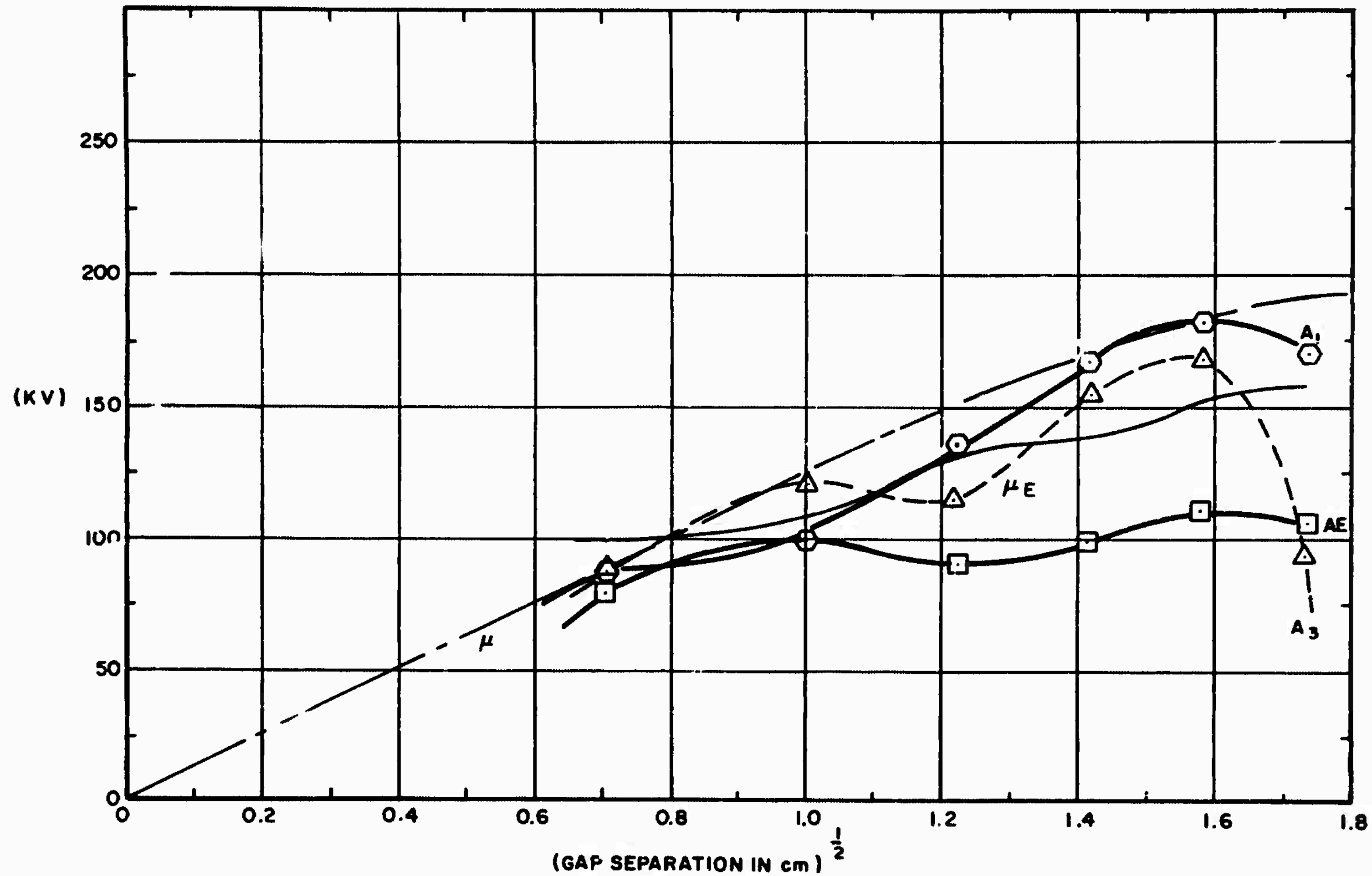

Figure 7. Anode Processing (A)

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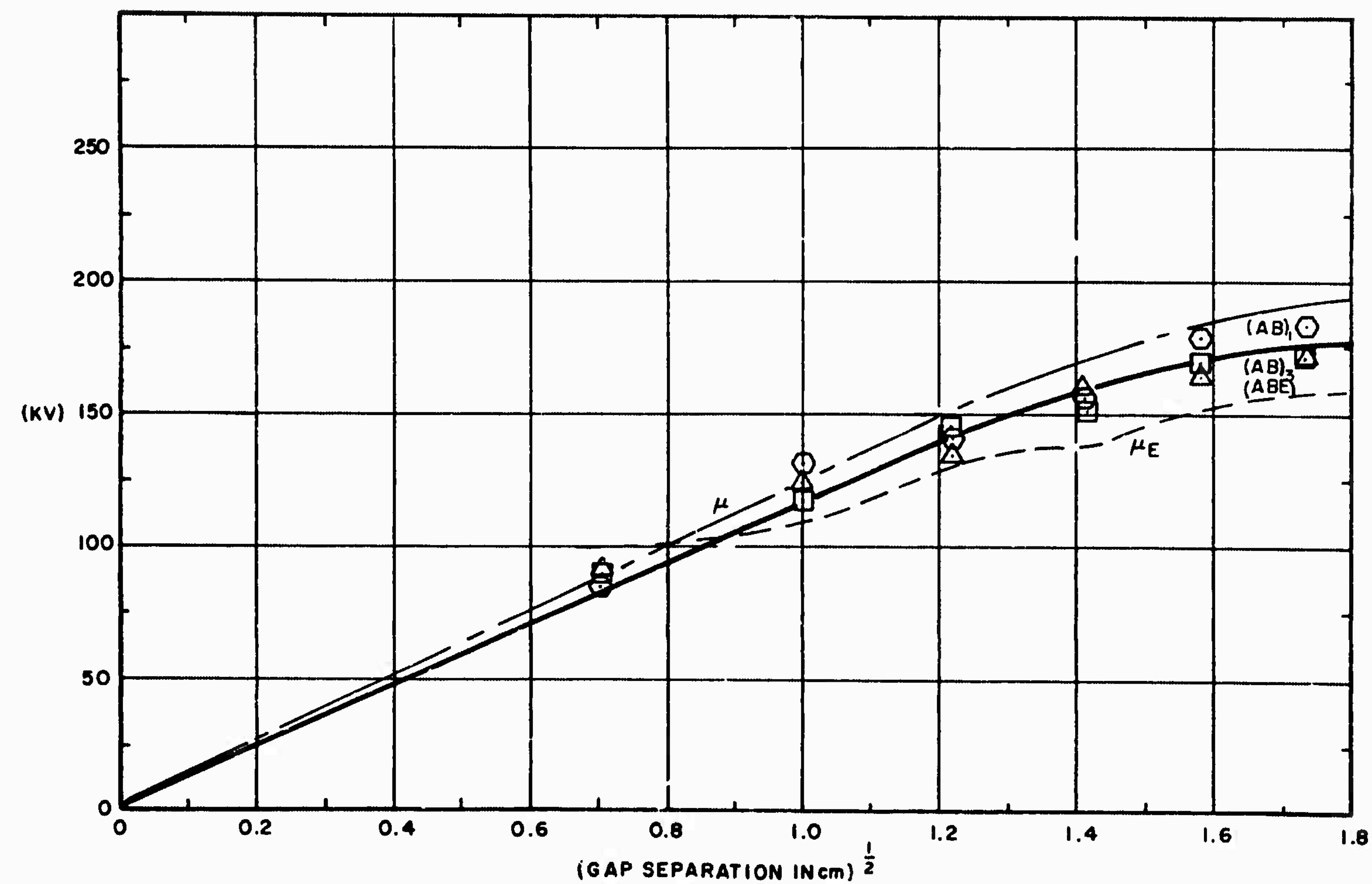

Figure 8. Anode Processing x Cathode Processing (AB)

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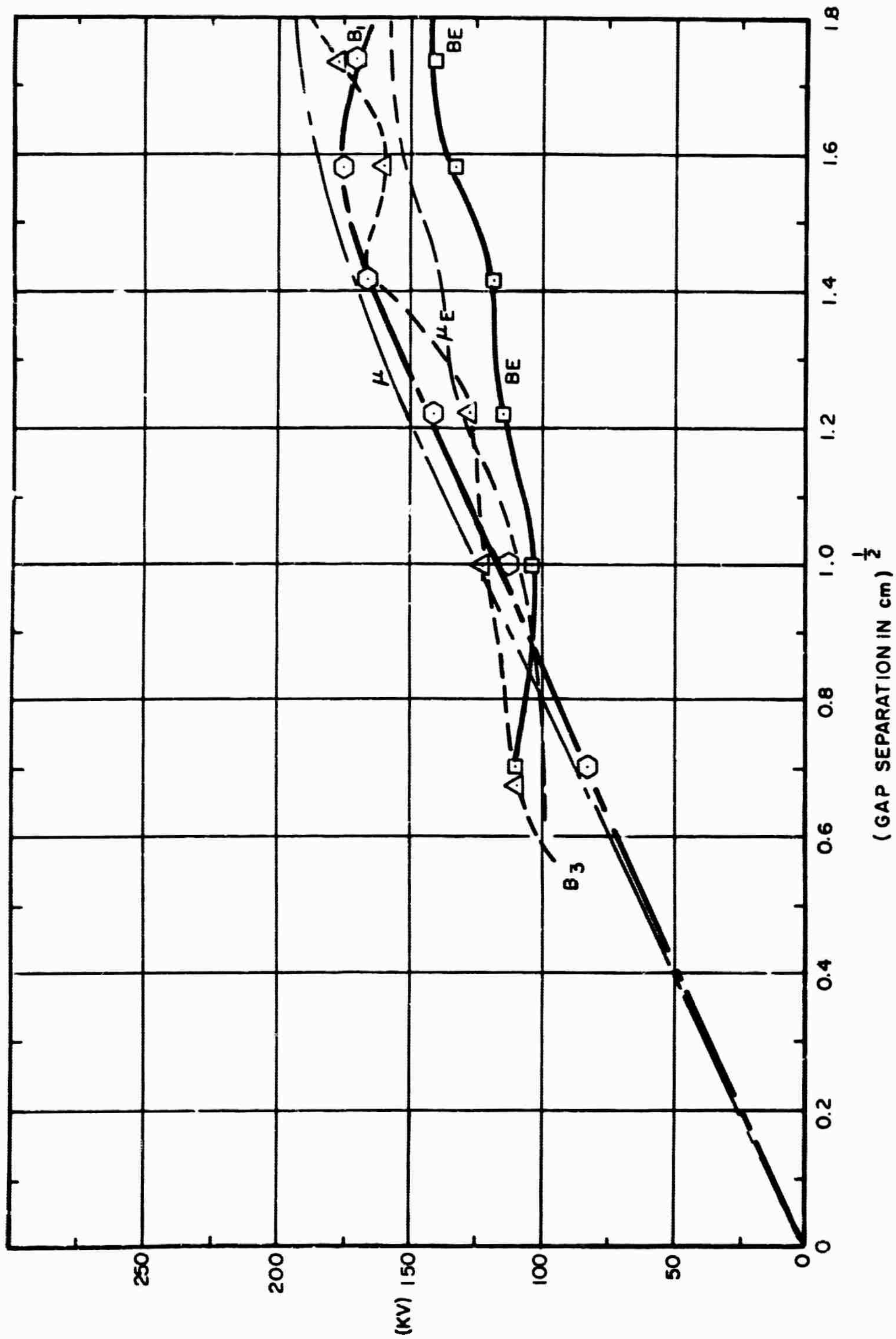

Figure 9. Cathode Processing (B)

1-2224

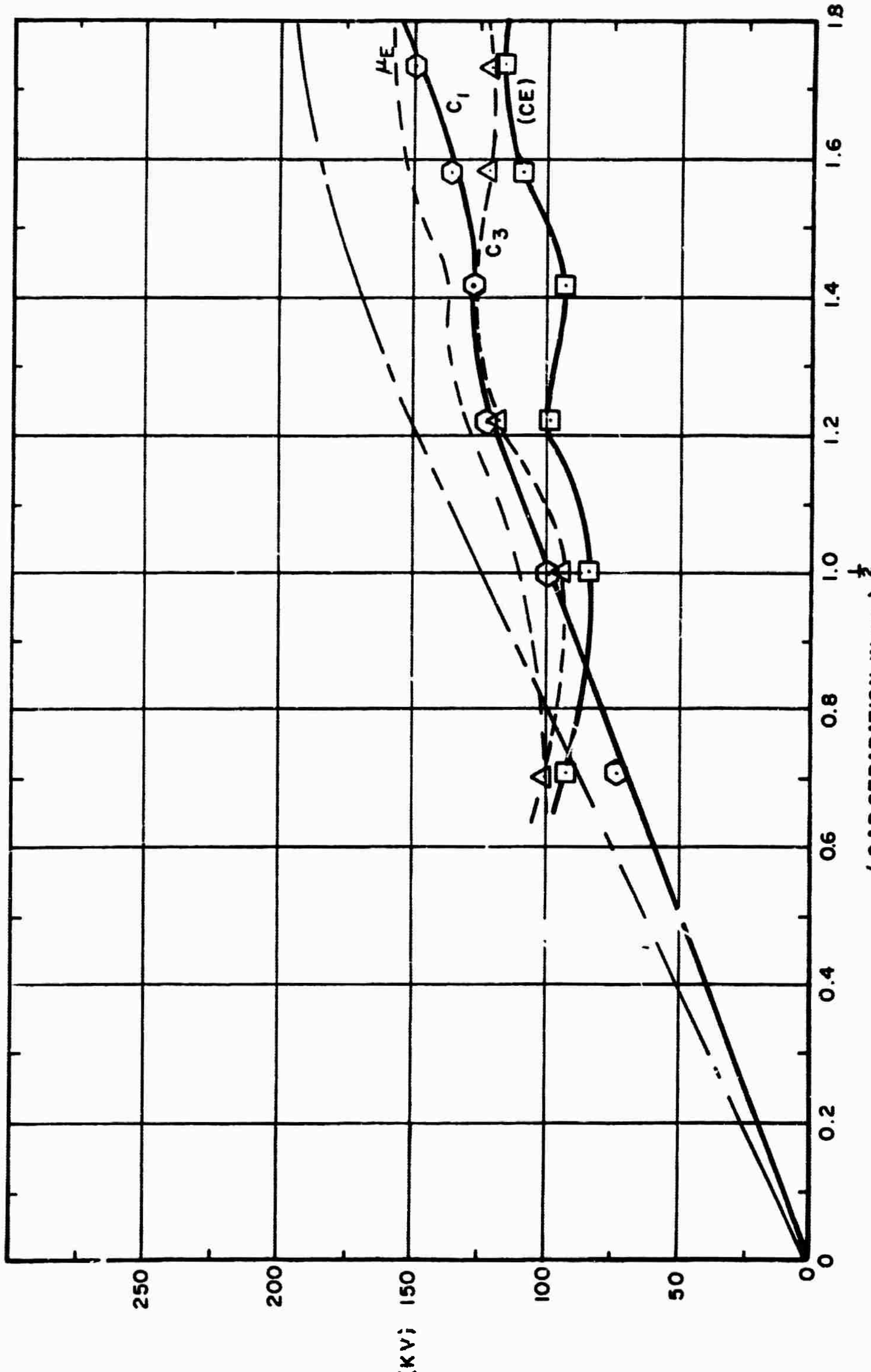

Figure 10. Electrode Size (C)

1-2225

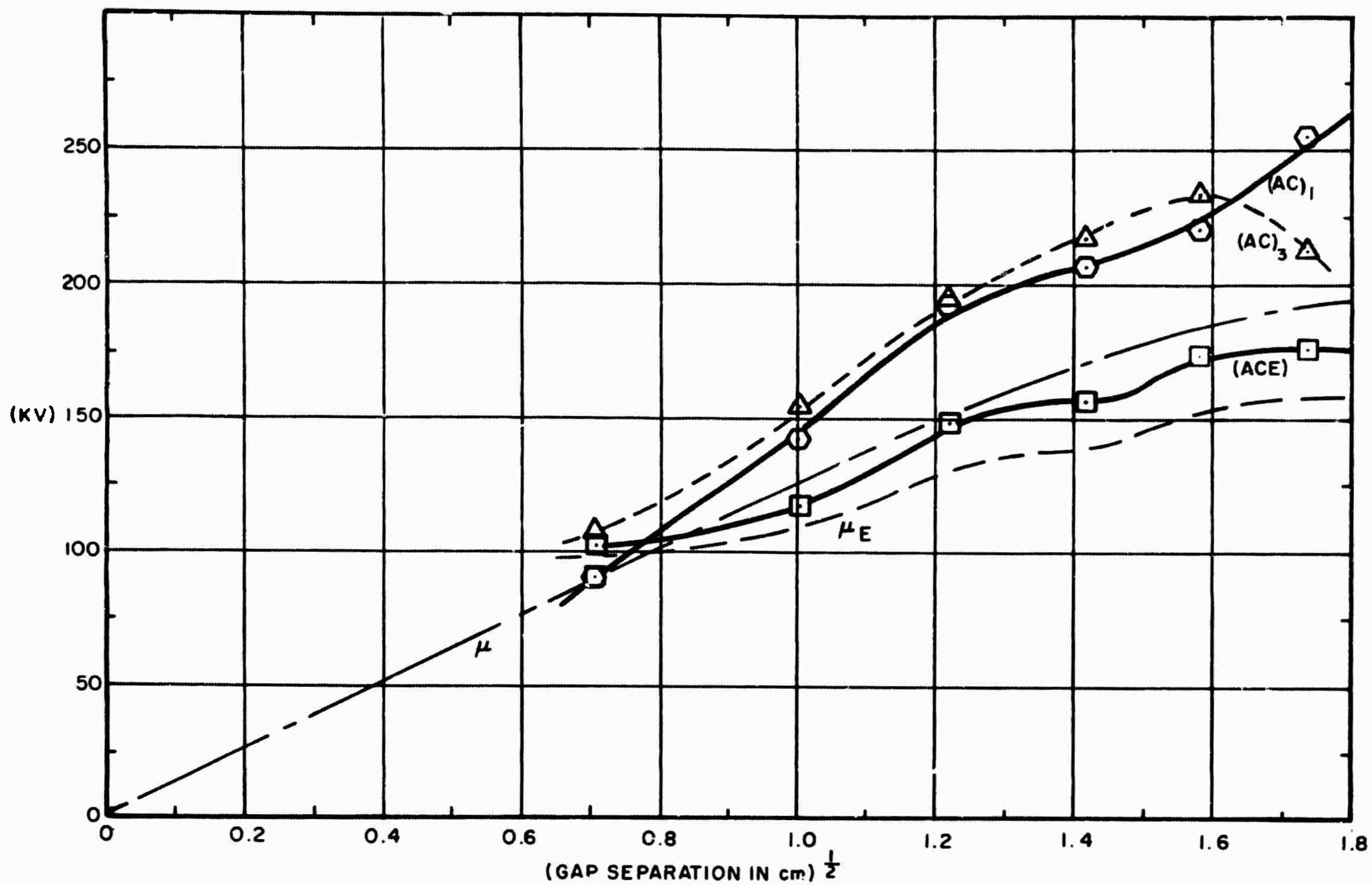

Figure 11. Anode Processing x Electrode Size (AC)

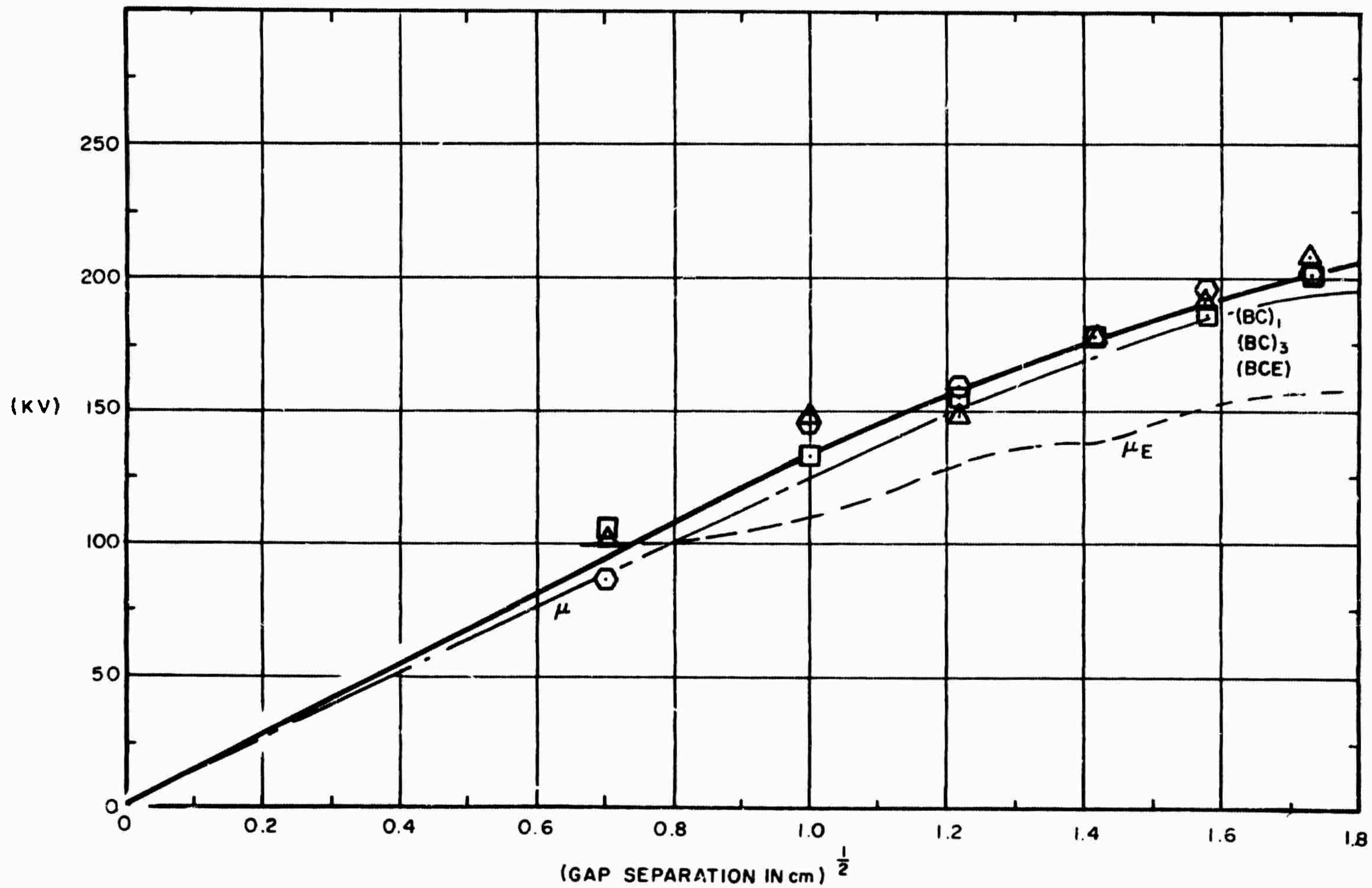

Figure 12. Cathode Processing x Electrode Size (BC)

1-2227

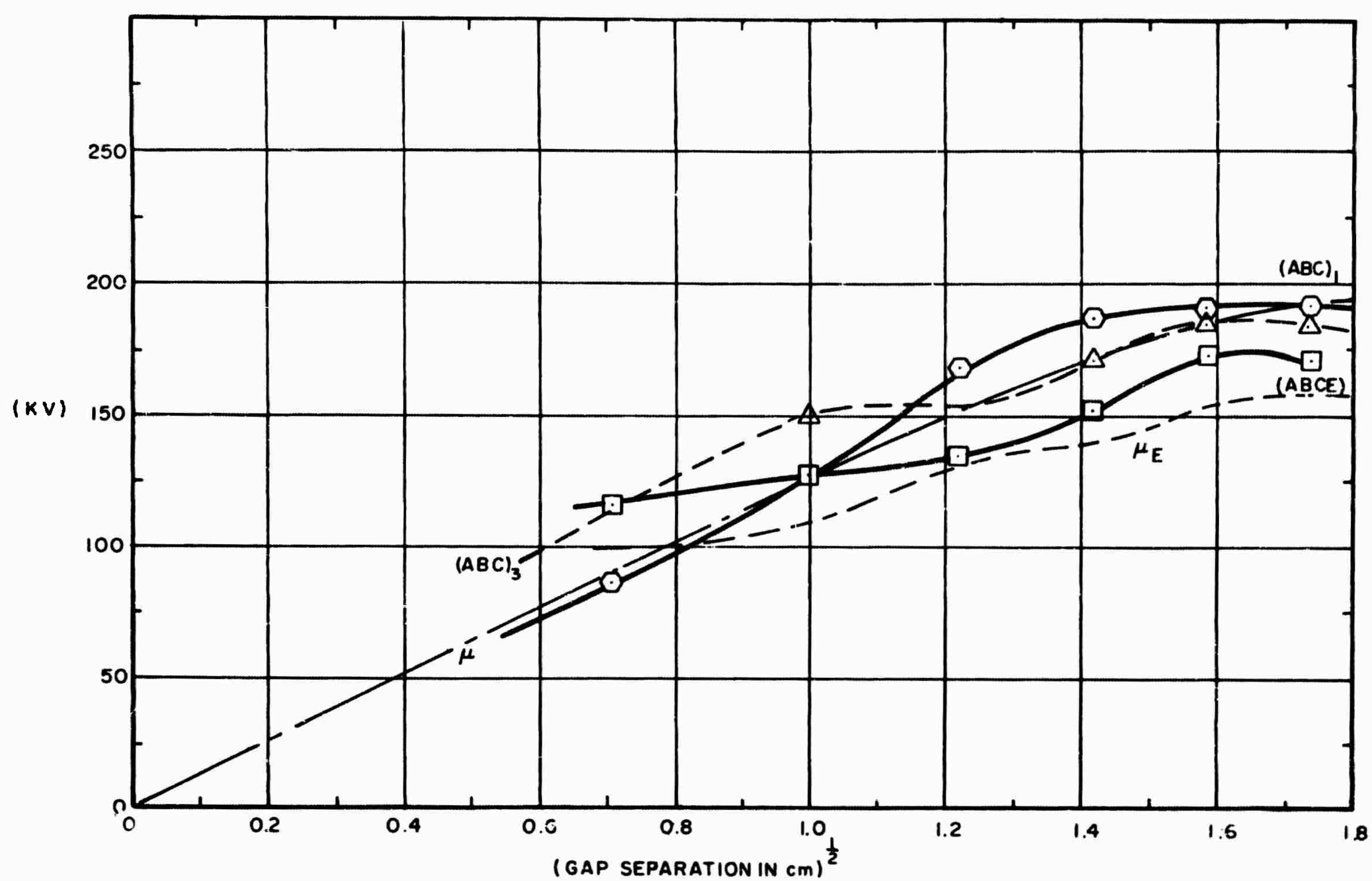

Figure 13. Cathode Processing x Anode Processing x Electrode Size (ABC)

A most significant effect is that the magnetic field reduces the average breakdown voltage (curve μ to curve μE). There is a gap separation, however, below which the breakdown voltage is raised.

The interactions of each of the factors with the magnetic field will now be discussed separately.

4.2.2 Anode Processing

Anode processing lowers the breakdown voltage below average for larger gaps, but the effect is small until the magnetic field is applied and the drop is then significant. After this, a memory of the effect lingers on for large gaps.

There is no gap separation crossover point for the sign of the magnetic field such as there is for the μ and μH effects between 0.5 and 1.0 cm.

4.2.3 Cathode Processing

Cathode processing lowers the breakdown voltage by too slight an amount to be significant, but it is consistent and the magnetic field amplifies it.

The magnetic field still appears to exert a memory effect. There is no definite gap separation crossover point between the BE and B_3 curves.

Thus, there is an interaction between magnetic field and cathode processing.

4.2.4 The Interaction of Anode Processing and Cathode Processing (AB)

There is practically no difference between (μ - AB) or (μ - ABE) and the average breakdown voltage μ and μH. The random order of $(AB)_1$, $(AB)_3$ and (ABE) shows that there is absolutely no effect at all either with or without magnetic field.

4.2.5 Electrode Area

(1) This is by far the greatest contribution, large electrodes lowering V_B by up to about 20% at 3 cm gap.

(2) The reduction is about the same whether or not the magnetic field is present

(3) The crossover point is not changed and the effect is a uniform percentage lowering of V_B at all gaps.

(4) In view of (2), there is no interaction of electrode area and magnetic field.

4.2.6 The Interaction of Cathode Processing and Electrode Size (BC)

Again, as with AB, there is no effect evident.

4.2.7 The Interaction of Anode Processing and Electrode Size (AC)

The combination of hydrogen baked anode and small electrodes contributes by raising the breakdown voltage. The amount by which AC raises the voltage above the average is different in the presence of the magnetic filed and it must therefore be concluded that there is an interaction with the magnetic field as a factor (factor E).

4.2.8 The Interaction of Anode and Cathode Processing and Electrode Size, (APC)

This interaction is small but the amount by which the breakdown voltage is raised above the corresponding average (μ or μE) increases with the application of magnetic field and so it must be concluded that there is an interaction with the magnetic field, although small.

SECTION 5

DESIGN OF NEXT EXPERIMENT

Preliminary discussions have been held on the factors for and design of the next experiment. At the moment it appears that it may be a 32 treatment full factorial experiment with probably 6 inflexible factors and 4 flexible factors. These factors may be as follows:

Inflexible	Flexible
Anode Material	Gap
Cathode Material	Magnetic Field
Geometry (1)	Exposure
Geometry (2)	Energy Storage
Overall Treatment	
Dielectric Envelope	

This could give a main 32 treatment half factorial experiment of 6 factors at 2 levels, with 3 or more stacked parallel experiments using the flexible factors. This design and the factors selection will be decided upon early in the next quarter.

SECTION 6

FUTURE EFFORT

During the next quarter it is intended to:

- Continue analysis of block of eight experiment.
- Continue analysis of pilot experiment.
- Select factors and levels for next experiment.
- Finalize design of next experiment.
- Commence statistical designed experiment.
- Check and commission energy storage system.
- Complete design of dielectric envelope system.
- Maintain 300 kv system in operational state.
- Carry out relevant side experiments.
- Fabricate electrodes.

SECTION 7

IDENTIFICATION OF PERSONNEL

The following personnel were active in the program during the period under review:

A. S. Denholm	- Department Manager
M. J. Mulcahy	- Project Manager
A. C. Stewart	- Engineering Manager
W. R. Bell	- Electrical Engineer
G. K. Simcox	- Electrical Engineer
M. M. Thayer	- Metallurgist
A. Watson	- Physicist
R. M. Parsons	- Engineering Aide
R. Benoit	- Design Engineer
C. Boudreau	- Engineering Aide
R. Comeau	- Vacuum Technician
L. Indingaro	- Metallurgical Technician
F. Battistello	- Technician
Prof. H. Freeman	- Consultant Massachusetts Institute of Technology Department of Economics and Social Science
Prof. A. Argon	- Consultant Massachusetts Institute of Technology Department of Mechanical Engineering
Dr. N. E. Woldman	- Consultant Metallurgy

APPENDIX A

NOTES ON METHODS OF CONSTRUCTING FRACTIONAL FACTORIAL DESIGNS

by

Harold Freeman
Massachusetts Institute of Technology

NOTES ON METHODS OF CONSTRUCTING FRACTIONAL FACTORIAL DESIGNS*

A. 1 The Complete Factorial 2^2

Consider 2 factors A and B each at 2 levels + and -. Consider a complete factorial design. There will be $2^2 = 4$ treatment combinations and, consequently, 4 data points. The situation is shown in Table 1.

Table 1

Treatment Combination	Level of A	Level of B	Data Point
(1)	-	-	Y_1
a	+	-	Y_2
b	-	+	Y_3
ab	+	+	Y_4

As we know, Table 1 also guides us as to the algebraic signs of the terms in the estimates of effects A and B. Thus:

$$A = \frac{1}{2}(-Y_1 + Y_2 - Y_3 + Y_4)$$

or

$$\frac{1}{2}(-(1) + a - b + ab)$$

$$B = \frac{1}{2}(-Y_1 - Y_2 + Y_3 + Y_4)$$

or

$$\frac{1}{2}(-(1) = a + b + ab)$$

*These notes borrow examples from Davies', The Design and Analysis of Industrial Experiments.

But, as we know, 4 points permit estimation of 3 effects as well as μ, in this example:

A, B, AB, μ

As we know, the algebraic signs in the estimate of AB are the products of the corresponding signs for A and B:

$$AB = \frac{1}{2} (Y_1 - Y_2 - Y_3 + Y_4)$$

or

$$\frac{1}{2} ((1) - a - b + ab)$$

while in the estimate of the overall mean μ, all signs are positive (the products of the signs of all effects, A, B, and AB):

$$\mu = \frac{1}{4} (Y_1 + Y_2 + Y_3 + Y_4)$$

or

$$\frac{1}{4} ((1) + a + b + ab)$$

and Table 1 can be enlarged to become Table 2.

Table 2

Treatment Combination	A	B	AB	μ	Data Point
(1)	-	-	+	+	Y_1
a	+	-	-	+	Y_2
b	-	+	-	+	Y_3
ab	+	+	+	+	Y_4

A. 2 The Half-Factorial 2^{3-1}

All this relates to the complete factorial 2^2. Now assume interaction AB = 0. As 4 data points always permit estimation of 3 effects* (other than μ), we can now estimate an additional factor, say C, in place of the non-existent AB. We "equate" C to AB and write C = AB. Table 2 is altered to become Table 3.

Table 3

Treatment Combination	A	B	C = AB	μ	Data Point
c	-	-	+	+	Y_1
a	+	-	-	+	Y_2
b	-	+	-	+	Y_3
abc	+	+	+	+	Y_4

*Notice that with 4 data points Y_1, Y_2, Y_3, Y_4, three independent contrasts, for example,

Estimate of A	$-Y_1 + Y_2 - Y_3 + Y_4$
Estimate of B	$-Y_1 - Y_2 + Y_3 + Y_4$
Estimate of AB	$Y_1 - Y_2 - Y_3 + Y_4$

can be formed; one cannot get any one of these contrasts from the other two by addition or multiplication. But any 4th contrast, say

$$-Y_1 + Y_2 + Y_3 - Y_4$$

or

$$-Y_1 - Y_2 - Y_3 + Y_4$$

can be obtained by operations on the first three, and so is not independent of them.

Note, of course, that the 4 new treatment combinations are different; one cannot estimate C by any manipulation of the original treatment combinations:

(1) a b ab

The 4 new treatment combinations are determined simply from the signs in the A, B and C columns. For example, for the first data point Y_1, factor A is -, factor B is -, and new factor C is +, this treatment combination is c. Summarizing:

with C = AB, treatment combinations are c a b abc.

If we introduced C via C = -AB, we would have Table 4.

Table 4

Treatment Combination	A	B	C = -AB	μ = ABC	Data Point
(1)	-	-	-	+	Y_1
ac	+	-	+	+	Y_2
bc	-	+	+	+	Y_3
ab	+	+	-	+	Y_4

and the summary would evidently have been

with C = -AB, treatment combinations are (1) ac bc ab

In Tables 3 and 4 we have 3 factors, A, B and C each at 2 levels. It would require $2^3 = 8$ data points to estimate all 8 effects.

μ A, B, C, AB, AC, BC, ABC.

We have only 4 data points - a half-factorial design written 2^{3-1}. As all 8 effects above may exist (may be non-zero), our estimates from 4 data points, of the main effects

μ A, B, C

will be confounded by AB, AC, BC, ABC, if in fact the latter exist. As we already know, if AB does exist then from Table 3

c - a - b + abc estimates C + AB

Also, further examining Table 3, it will be seen that the algebraic signs in the A column are the products of the corresponding signs in the B and C columns. So if in fact interaction BC exists, we are estimating with this half-factorial design not A but

A + BC

Finally, in Table 3, the signs in the B column are the products of the corresponding signs in the A and C columns. So if in fact interaction AC exists, we are estimating

B + AC

A similar examination of Table 4 indicates that if we create the half factorial design by equating C to -AB, we will be estimating

C - AB, A - BC, B - AC

A. 3 The Complete Factorial 2^3

Now consider 8 data points Y_1, Y_2, ... Y_8. If we have 3 factors A, B and C each at two levels + or -, these 8 data points are sufficient to estimate all main effects and all interactions. We have the familiar Table 5, here slightly rearranged for present purposes.

Table 5

Treatment Combination	A	B	C	AB	AC	BC	ABC	μ	Data Point
(1)	-	-	-	+	+	+	-	+	Y_1
a	+	-	-	-	-	+	+	+	Y_2
b	-	+	-	-	+	-	+	+	Y_3
ab	+	+	-	+	-	-	-	+	Y_4
c	-	-	+	+	-	-	+	+	Y_5
ac	+	-	+	-	+	-	-	+	Y_6
bc	-	+	+	-	-	+	-	+	Y_7
abc	+	+	+	+	+	+	+	+	Y_8

The treatment combinations in column 1 correspond to the signs of A, B and C; thus for data point Y_1, factor A is -, factor B is -, and factor C is -, and the corresponding treatment combination is (1). Also, as you know, Table 5 provides a guide to the algebraic signs in our estimates of the effects; thus, for example, in estimating the main effect A,

$$A = \frac{1}{4} (-Y_1 + Y_2 - Y_3 + Y_4 - Y_5 + Y_6 - Y_7 + Y_8)$$

or

$$\frac{1}{4} (-(1) + a - b + ab - c + ac - bc + abc)$$

A. 4 The H ctorial 2^{4-1}

In a 3 factor situation, assume ABC = 0. Si ce 8 data points always permit estimation of 7 effects (as well as μ), we now can estimate, in place of ABC, a new factor, say D. If we write

$$D = ABC$$

the four columns A, B, C, D will determine the appropriate 8 treatment combinations -a half-factorial 2^{4-1}. This is shown in Table 6.

Table 6

Treatment Combination	A	B	C	D	Data Points
(1)	-	-	-	-	Y_1
ad	+	-	-	+	Y_2
bd	-	+	-	+	Y_3
ab	+	+	-	-	Y_4
cd	-	-	+	+	Y_5
ac	+	-	+	-	Y_6
bc	-	+	+	-	Y_7
abcd	+	+	+	+	Y_8

Thus, for example, for data point Y_3, factor A is -, factor B is +, factor C is - and factor D is +, and the corresponding treatment combination is bd. And, as before, by examination of Table 6, the signs of various effects are identical and therefore they along with D and ABC (already noted) will be confounded in the estimation process. To illustrate, the 8 signs in the B column are the same as the product of the signs in the A, C and D columns. Thus B and ACD are confounded. As a second illustration, the product of the signs in the A and B columns is the same as the product of the signs in the C and D columns. So AB and CD are confounded. In summary, of the sixteen effects which exist in a four factor experiment,

μ
A, B, C, D
AB, AC, BC, AD, BD, CD
ABC, ABD, ACD, BCD
ABCD

only eight effects can be estimated by the 8 data points of the half factorial 2^{4-1}, and they are (the confounded effects)

μ + ABCD
A + BCD
B + ACD
C + ABD
D + ABC
AB + CD
AC + BD
AD + BC

As we shall soon see these can be reached much more quickly than by the noting which operations in Table 6 yield identical signs.

If in fact all or most of these interactions are not negligible, the half-factorial 2^{4-1} is surely a questionable design.

Entirely similarly, if we began with

$$D = -ABC$$

Table 6 would be replaced by Table 7.

Table 7

Treatment Combination	A	B	C	D	Data Points
d	-	-	-	+	Y_1
a	+	-	-	-	Y_2
b	-	+	-	-	Y_3
abd	+	+	-	+	Y_4
c	-	-	+	-	Y_5
acd	+	-	+	+	Y_6
bcd	-	+	+	+	Y_7
abc	+	+	+	-	Y_8

and the resulting eight treatments combinations would be those shown in the first column. The confoundings would be

μ - ABCD
A - BCD
B - ACD
C - ABD
D - ABC
AB - CD
AC - BD
AD - BC

no better or worse than the confoundings resulting from D = ABC. It is therefore a matter of convenience whether, in a 2^{4-1} fractional design, one uses in the eight treatment combinations in the first column of Table 6 or those in the first column of Table 7; sometimes certain treatment combinations are readily available, or are easier to create than others. This has happened at Ion Physics.

A. 5 The Quarter Factorial 2^{5-2}

With 8 data points, consider the complete 2^3 factorial, this time with two interactions assumed to be 0. Using an example from Davies, assume

ABC = 0
BC = 0

Now, in addition to D which was introduced when we assume ABC = 0, another factor E can be introduced. Table 5 becomes Table 8.

Table 8

Treatment Combination	A	B	C	D	E
e	-	-	-	-	+
ade	+	-	-	+	+
bd	-	+	-	+	-
ab	+	+	-	-	-
cd	-	-	+	+	-
ac	+	-	+	-	-
bce	-	+	+	-	+
abcde	+	+	+	+	+

where D takes on the signs of ABC in Table 5, and E takes on the signs of BC in Table 5. The treatment combinations in the first column follow from the signs of A, B, C, D, E. Thus for the first data point Y_1, factor A is -, B is -, C is -, D is - and E is +; this is treatment combination e.

We are here dealing with 5 factors for which a complete factorial would require $2^5 = 32$ data points. As we have only 8 data points, the design is a quarter factorial, often written 2^{5-2}. There are 3 other 2^{5-2} designs and they are obtained simply by changing, in Table 8, all the signs of D, all the signs of E, and finally all the signs of both. The four designs thus correspond to

$$D = \pm ABC$$
$$E = \pm BC$$

All four are given in Table 9.

Table 9

D = ABC, E = BC

Treatment Combination	A	B	C	D	E
e	-	-	-	-	+
ade	+	-	-	+	+
bd	-	+	-	+	-
ab	+	+	-	-	-
cd	-	-	+	+	-
ac	+	-	+	-	-
bce	-	+	+		+
abcde	+	+	+	+	+

D = -ABC, E = BC

Treatment Combination	A	B	C	D	E
de	-	-	-	+	+
ae	+	-	-	-	+
e	-	+	-	-	-
abd	+	+	-	+	-
c	-	-	+	-	-
acd	+	-	+	+	-
bcde	-	+	+	+	[illegible]
abce	+	+	+	-	+

Table 9 (Continued)

$D = ABC$, $E = -BC$

Treatment Combination	A	B	C	D	E
(1)	-	-	-	-	-
ad	+	-	-	+	-
bde	-	+	-	+	+
abe	+	+	-	-	+
cde	-	-	+	+	+
ace	+	-	+	-	+
bc	-	+	+	-	-
abcd	+	+	+	+	-

$D = -ABC$, $E = -BC$

Treatment Combination	A	B	C	D	E
d	-	-	-	+	-
a	+	-	-	-	-
be	-	+	-	-	+
abde	+	+	-	+	+
ce	-	-	+	-	+
acde	+	-	+	+	+
bcd	-	+	+	+	-
abc	+	+	+	-	-

In a complete 2^5 design with 32 data points 32 effects (including μ) can be estimated. As there are 32 effects in a 5-factor experiment no matter how many data points are available to estimate them, it follows that with only 8 data points, and with any one of these four designs in Table 9, four effects must always be confounded in each estimate. To determine which effects are confounded we can proceed as in Section A-2 of these notes, noting which combinations of factors have the same signs as others. A simpler procedure is to

create the defining contrast and work from it. In the upper left design of Table 9 we have

$$D = ABC, \quad E = BC$$

Multiplying the first equality through by D and the second by E, we have, since $D^2 = E^2 = I$,

$$I = ABCD \quad I = BCE$$

and since their product (interaction) is also I, we have the defining contrast

$$I = ABCD = BCE = ADE$$

From this, by multiplication, the remaining 7 confounded or confused effects can be found, as follows.

Table 10

Multiply By	Confounding
A	A = BCD = ABCE = DE
B	B = ACD = CE = ABDE
C	C = ABD = BE = ACDE
D	D = ABC = BCDE = AE
E	E = ABCDE = BC = AD
AB	AB = CD = ACE = BDE
AC	AC = BD = BE = CDE

Any other multiplication will reproduce one of the confoundings above, as you can determine by trial.

The decision to use the 2^{5-2} design based on

$$D = ABC$$

and

$$E = BC$$

or better, on the defining contrast

$$I = ABCD = BCE = ADE$$

is usually based on examination of the confoundings shown in Table 10, as well as, of course, on the confounding shown in the defining contrast itself. If these are serious liabilities, for example, if it is believed that C is an important and non-zero main effect and BE is an important and non-zero interaction, the above design is questionable since it confounds C and BE, as evidenced in the third line of Table 10. These are the kinds of considerations which should precede adoption of any design.

The other 3 designs in Table 9 will do no better. The only difference will be that some of the signs in Table 10 will become negative. But the same confoundings will occur since the defining relation is the same as the one above except for signs.

APPENDIX B

APPLICATION OF STATISTICAL DESIGN TO HIGH VOLTAGE VACUUM BREAKDOWN

by

A. Watson and M. J. Mulcahy

APPLICATION OF STATISTICAL DESIGN TO HIGH VOLTAGE VACUUM BREAKDOWN

[illegible]. Watson and M. J. Mulcahy
Ion Physics Corporation, U.S.A.

INTRODUCTION

A statistically designed experiment has been initiated to study the factors which affect breakdown in vacuum in the range 100 to 300 kV. The need for this has been generated by present day requirements for extremely high power tubes, particularly since there are insufficient data available to permit a straightforward approach to the design of the high voltage section of these tubes. The statistical design was selected because it provides a powerful tool for the analysis of the results and enables the maximum information to be derived from a minimum number of experiments on the effect of individual factors and as many of the joint effects of two or more factors as are required.

APPARATUS FACTORS AND EXPERIMENT

The apparatus is shown in Figure 1. This has been described previously[1] and, therefore, it is sufficient now to indicate that the vacuum chamber consists of a 36-inch diameter, 304 stainless steel sphere. All flanges and ports are gold or copper o-ring sealed and the system was ion pumped down to the mid or low 10^{-8} torr range, depending on whether the electrodes only or the complete system was baked to 400°C prior to testing. Two electrode materials were used, namely OFHC copper and forged Ti-7Al-4Mo. The electrodes were 3 inches in diameter and either spherical or Bruce profile.

The program was initiated with a seven factor, two level quarter replicate partial factorial experiment consisting of 32 runs or treatments and 16 replications, thus yielding all main factor reactions and all but 6 of the 21 two-factor interactions. The order of the treatments was determined in a random manner and the factors and levels are shown in Table I. These factors were chosen on a basis of potential importance and the simplicity with which they could be varied. For each treatment, the unconditioned and conditioned breakdown parameters for 6 gaps in the range 0.5 to 3.0 cm were determined.

RESULTS AND STATISTICAL ANALYSIS

A computer program was drawn up to facilitate the statistical analysis. This provided the Yates Algorithm and hence the factor and interaction effects of interest for the various gaps. From these, half normal plots were constructed to enable the significant trends to be more easily distinguished. Figures 2 and 3 illustrate these plots for the 2.0 cm gap, both unconditioned and conditioned.

Within each of the half normal plots, particularly for unconditioned gaps, no factor or interaction effect takes on sharp significance. However, when all the plots are considered together the following noteworthy trends emerge:

(a) Unconditioned Gaps

(1) B is important. The effect of B is negative.

(2) AD is important. The effect of AD is positive.

(3) E is important at small gap size. Its importance declines as gap size increases. The effect of E is negative.

(4) D is important, perhaps more important as gap size increases. The effect of D is negative.

(5) CD may be important, except at largest gap size. The effect of CD is positive.

(6) C is unimportant at low gap size, important as gap size increases. The effect of C is negative.

(7) EF is important at low gap size, important as gap size increases. The effect of EF is positive.

(b) <u>Conditioned Gaps</u>

(1) A is important, possible of declining importance as gap size increases. The effect of A is negative.

(2) E is important, increasingly so as gap size increases. The effect of E is negative.

(3) B is fairly important. The effect of B is negative.

(4) D is important at larger gap sizes. The effect of D is negative.

The trends appearing in this statistical analysis confirm theoretical ideas developed partly during the program. Basically, a beam of field emitted electrons is envisioned as the precursor which releases gas from the anode. The gas accumulates on the beam axis at an average number density depending on both the electrode geometry and gap separation. Ionization by the primary beam then leads to an unstable condition leading to breakdown. The total ionization depends on the product of gas density along the beam and gap separation, but in a manner depending on the field distribution.

In consequence of this, the factors expected to be of significance would be anode material, bakeout, shape of both electrodes, and gap separation, all of which figure prominently in the results of the pilot experiment.

An interesting point is that anode material appears as a promiment single factor for conditioned electrodes, but appears only as an interaction with bakeout for the unconditioned case. Conditioning is pictured in the present theory to be the process of removal of gas from the surface

layers on the anode. Before conditioning, however, the density of sorbed gas at the surface will be the main factor which is more a function of bakeout.

Bakeout is consistently important in both conditioning states and increasingly so as gap separation increases. It thus may assume even greater importance than the anode material at large gap separations.

Both anode and cathode geometries are prominent factors in each case, but they appear to everse their rank of importance. Anode geometry moreover changes from having less importance at large gaps to the reverse after conditioning has taken place.

It is difficult to draw conclusions from these trends because electrode geometry and gap separation affect the pumping conductance, electric field distribution and ionization efficiency simultaneously. In a subsidiary experiment, this ambiguity is expected to be removed by studying uniform field electrodes only, thus removing the electrode shape as a factor.

Finally, cathode material and electrode finish do not appear prominently as factors. There appears to be a cathode material trend for unconditioned electrodes but little can be said about it with certainty.

REFERENCES

(1) Mulcahy, M. J. et al. Designed Experiments on High Voltage Vacuum Breakdown. Proceedings, Second International Symposium on Insulation of High Voltages in Vacuum, P. 103, (1966)

ACKNOWLEDGEMENTS

The authors wish to acknowledge helpful discussions with A. S. Denholm, G. W. Taylor, M. M. Chrepta and M. H. Zinn. They also wish to thank J. Weinstein and H. Freeman for drawing up the statistical design and carrying out the analysis, R. Parsons for assistance in carrying out the experiment and M. M. Thayer and C. Boudreau in designing and maintaining the apparatus.

*Sponsored by the Advanced Research Projects Agency under Contract DA-28-043-AMC-00394(E), ARPA Order No. 517.

Table 1. Factors and Levels for Pilot Experiment

Factors	Letters	Levels
Cathode Material	C	1 - Ti-7 Al-4 Mo
		c - OFHC Cu
Cathode Finish	G	g - Fine
		1 - Coarse
Cathode Geometry	B	b - Bruce Profile
		1 - Sphere
Bakeout	D	1 - Complete System Bakeout
		d - Electrode Bakeout Only
Anode Material	A	1 - Ti-7 Al-4 Mo
		a - OFHC Cu
Anode Finish	F	f - Fine
		1 - Coarse
Anode Geometry	E	e - Bruce Profile
		1 - Sphere

The higher and lower factor levels are represented by the low case letter and numbered one respectively.

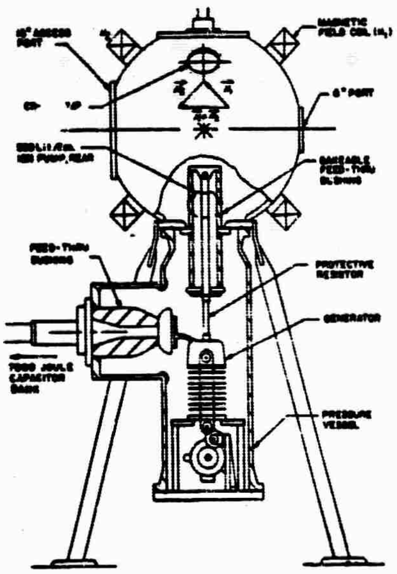

Figure 1. 300 kv Test Vehicle

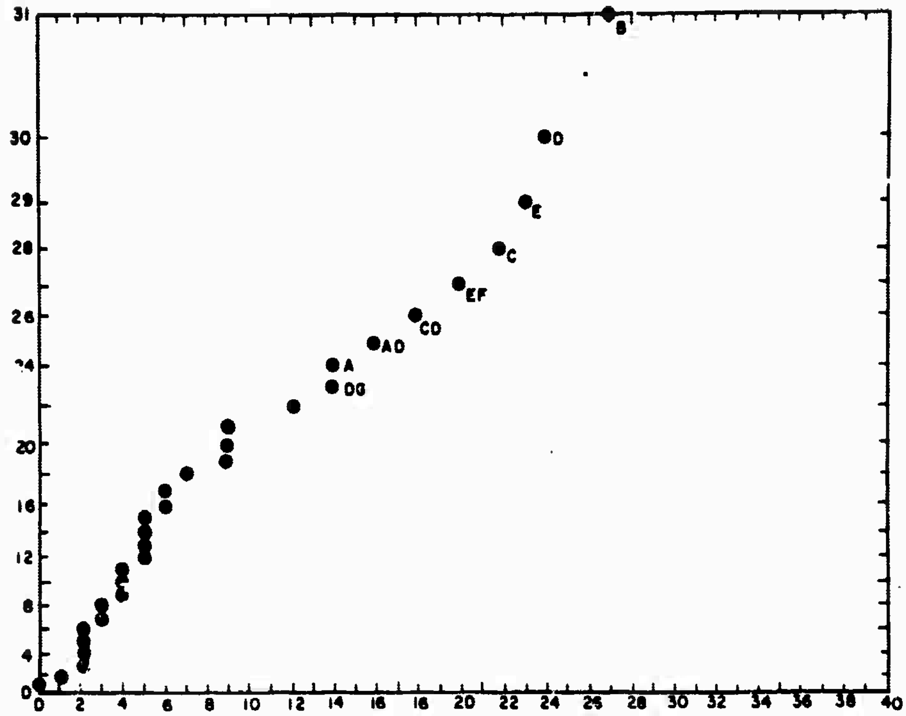

Figure 2. Half Normal Plot for 2.0 cm Unconditioned Gap

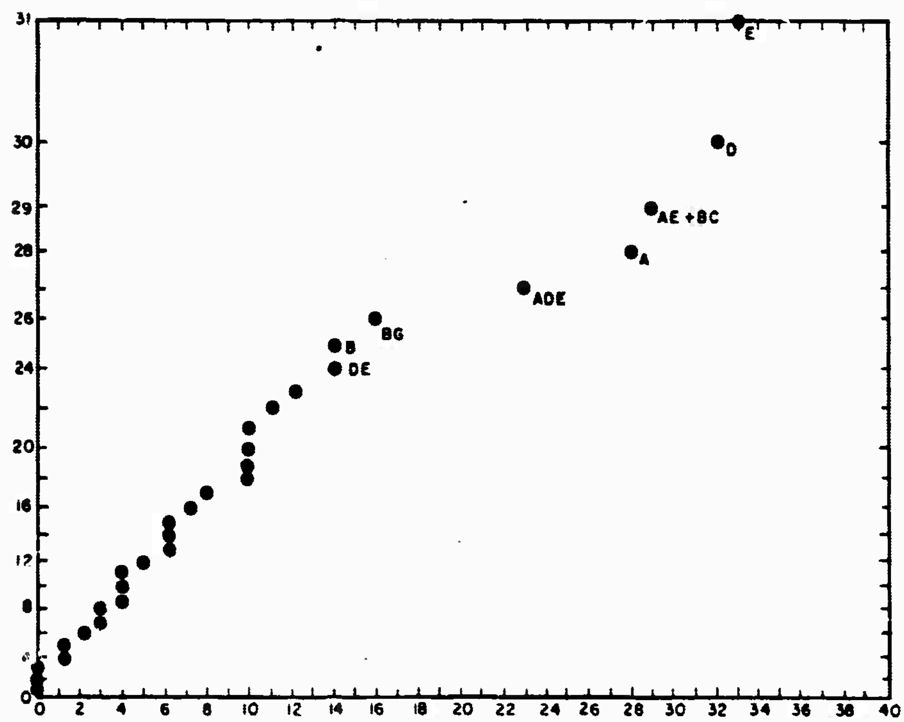

Figure 3. Half Normal Plot for 2.0 cm Conditioned Gap

APPENDIX C

HIGH VOLTAGE VACUUM BREAKDOWN IN A WEAK TRANSVERSE MAGNETIC FIELD

by

A. Watson, W. R. Bell and M. J. Mulcahy

HIGH VOLTAGE VACUUM BREAKDOWN IN A
WEAK TRANSVERSE MAGNETIC FIELD

by

A. Watson, W. R. Bell and M. J. Mulcahy

Ion Physics Corporation
Burlington, Massachusetts, U. S. A.

Conditions under which a weak (250 gauss) transverse magnetic field may influence breakdown voltage in vacuum have been studied in a three factor, two level factorial experiment. The power of this technique lies in its capability to differentiate joint effects of variables with the magnetic field. Parameters chosen for the experiment were electrode area and pretreatment by high temperature baking in either hydrogen or vacuum. The latter simulates brazing techniques used in tube manufacture as well as permitting a closer study of the involvement of hydrogen evolution in the breakdown process as has previously been reported.(1) Uniform field electrodes of different areas were chosen because they eliminate the influence of a variable field geometry. Any electrode size effect cannot thus be confounded by changes in electric field distribution from one electrode pair to another and over a range of gap separation.

Copper electrodes were smooth machined and polished with successive grades down to 600 grade emery paper. After degreasing they were fired for six hours at 900°C in either vacuum at $< 10^{-6}$ torr or in hydrogen at atmospheric pressure. They cooled to 200°C in their respective environments and dry nitrogen was admitted for transferring to the vacuum test chamber where a complete system bake at 400°C was carried out for six hours. Gas analysis of test samples showed that the hydrogen baked into them was 0. 35 ppm and fell to 0. 14 ppm after the second bake out.

A sequence of breakdown tests over a range of gap separation from 0. 5 to 3. 0 cm in 0. 25 cm increments was performed without any

previous conditioning. Immediately following this the procedure was repeated. These tests are arbitrarily referred to as "unconditioned" and "conditioned" simply because in the second series a fixed greater number of sparks (twelve) precedes each test than in the corresponding test in the first series. Following this the magnets were assembled and the breakdown observed at 0.5 cm intervals from 0.5 to 3.0 cm. At each separation the measurement was made without, with, and again without the magnetic field. Comparison was made between these results to observe the magnetic effect.

The principal conclusions to be reached from Table I with a good measure of confidence are as follows.

(1) The overall effect of the magnetic field was to reduce the average breakdown voltage.

(2) The hydrogen baking procedure permitted a higher breakdown voltage to be attained than did vacuum baking. The magnetic field amplified this difference. Hydrogen baking of the anode induced the third breakdown at each gap separation to lie close to the value with magnetic field present. It thus seemed to remember the conditions imposed by the magnetic field.

(3) Large area electrodes reduced the breakdown voltage and the magnetic field had no effect upon this.

(4) The combined effect of hydrogen baking of the cathode and using small electrodes raises the breakdown voltage and it is amplified in the presence of a magnetic field.

REFERENCE

(1) A. Watson, A. S. Denholm, and M. J. Mulcahy, "Prebreakdown Phenomena in Vacuum Gaps", Procs. 2nd Int. Symp. on Insulation of High Voltages in Vacuum, (September 1966).

Table I.

Yates. With magnetic field. Conditioned. Estimates of effects by Yates' algorithm. In the table below "no" indicates no field, "yes" indicates field.

	0.05			1.00			1.50			2.00			2.50			3.00		
	no	yes	no	no	yes	no	no	yes	no	no	yes	no	no	yes	no	no	yes	no
μ	87	99	102	126	108	129	149	130	146	169	137	170	185	151	180	192	155	183
A	0	-21	-16	28	-10	-9	-14	-41	-32	-3	-39	-15	-5	-43	-15	-24	-50	-40
B	-4	12	11	-14	-5	-6	-8	-15	-18	-3	-19	-5	-10	-18	-20	-21	-15	-5
AB	-2	-9	-9	5	10	-4	-9	15	-12	-13	14	-10	-6	18	-15	-9	15	-10
C	-14	-7	-6	-27	-25	-36	-27	-31	-28	-43	-45	-40	-50	-43	-60	-44	-40	-65
AC	4	4	4	17	10	26	44	19	48	38	20	45	36	-23	55	64	20	30
BC	0	7	1	19	25	19	10	25	2	8	40	5	11	38	10	11	45	25
ABC	-1	15	11	1	20	31	19	5	8	18	15	0	15	23	5	-1	15	0

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APPENDIX D

CONTROLLED EXPERIMENTS ON VACUUM BREAKDOWN

by

M. J. Mulcahy, A. S. Denholm and A. Watson

CONTROLLED EXPERIMENTS ON VACUUM BREAKDOWN*

by

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ABSTRACT

An experiment is described which was designed to study the factors influencing high voltage breakdown in vacuum, with particular application to problems encountered in the development of high power vacuum tubes. The first part was devoted to developing procedures for preparation and voltage conditioning of electrodes in vacuum with minimal sparking. The next objective was to determine if there was a generally reliable and consistant criterion which could be used to predict electrical breakdown of vacuum gaps without damaging the electrode surfaces. In pursuance of this, instrumentation and monitoring techniques were developed in order to describe the gap as fully as possible during the prebreakdown and breakdown stages. Thus, during stepwise application of voltage the following were monitored, microdischarge activity, gap current, both magnitude and waveshape, light output, partial pressure of hydrogen or nitrogen and X-radiation. For the second phase of the experiment the voltage range was extended to 300 kv using a stainless steel bakeable chamber. Also, a statistical design was chosen because it provides a powerful tool for the analysis of the results, and yields information from a minimum number of experiments on the effects both of selected individual factors and two-factor interactions. The first such experiment involving seven factors has been completed and the results analyzed both on a statistical and a physical basis. Some significant trends have emerged from the statistical analysis and encouragingly, these have been found to be consistent with theories of the mechanism of breakdown developed from the physical analysis.

* Sponsored by the Advanced Research Projects Agency under Contract DA-28-043-AMC-00394(E), ARPA Order No. 517.

APPENDIX E

ELECTRODE SIZE AND PRETREATMENT EFFECTS ON VACUUM BREAKDOWN IN A TRANSVERSE MAGNETIC FIELD

by

Alan Watson

ELECTRODE SIZE AND PRETREATMENT EFFECTS ON VACUUM BREAKDOWN IN A TRANSVERSE MAGNETIC FIELD.* ALAN WATSON, Ion Physics Corporation.

Large and small uniform field copper electrodes were initially fired at 900°C in either vacuum or hydrogen before transferring to a large vacuum test chamber for further bakeout at 400°C. A statistically designed experiment at 10^{-8} torr in which voltage was raised 10 kv every two minutes showed that from 0.75 to 3.0 cm, but not below this, the breakdown voltage and prebreakdown currents were both dramatically reduced by a 250 Gauss transverse magnetic field. Hydrogen firing and small electrodes, individually and in combination, enhanced the breakdown voltage with or without magnetic field present. An auxiliary experiment revealed that, for the same gap separation, the threshold for gas surges appearing was raised by the magnetic field. The corresponding current threshold was unaltered, but the ultimate prebreakdown current was reduced by the magnetic field. The evidence supports the theory that gas released from the anode at a critical current level accumulates according to the pumping conductance and the subsequent breakdown is facilitated by a weak transverse magnetic field.

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13. ABSTRACT

The block of eight experiments was completed during the reporting period. This consisted of the study of unconditioned and conditioned gaps in the range 0.25 to 3.0 cm and a parallel experiment to study the effect of the presence of magnetic field. Both physical and statistical analyses of the results have been carried out and have yielded very interesting trends which are consistent with the theories developed. The 300 kv apparatus has been completely overhauled and cleaned. The chamber and flanges were electro-polished, the electrode system redesigned and the bakeable bushing replaced. The Universal Voltronics and Van de Graaff power supplies were also overhauled and new baking and pumping systems designed, installed and commissioned. The new baking system provides for a consistent automated baking cycle for all future treatments. The design of the trigger unit for the energy storage crowbar has been completed. Finally, the preliminary design and selection of factors for the next experiment has been initiated.

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